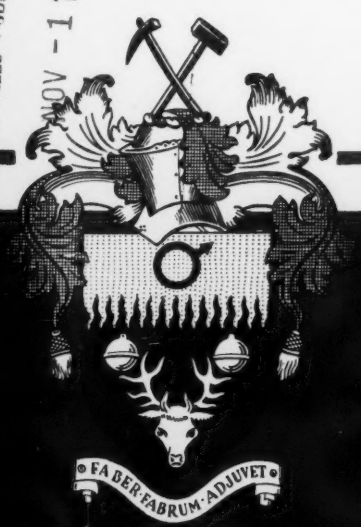
R
669.106
I 71
STACKS
Sci

SEPTEMBER 1950

JOURNAL OF THE IRON AND STEEL INSTITUTE

4 GROSVENOR GARDENS · LONDON · S·W·I

LOS ANGELES PUBLIC LIBRARY
NOV - 1 1950



Established 1869 · Incorporated by Royal Charter 1899

VOL. 166 PART I

Principal Contents

The Production of Steel Plates in Scotland
by J. A. Kilby

Distribution of Temperature in Ingot Moulds
by I. M. Mackenzie and A. J. Donald

Ingot Heat Conservation

Penetration of Molten Metal into Compacted Sand
by T. P. Hoar and D. V. Atterton

Use of Aluminium in Hot-Dip Galvanizing
by M. L. Hughes

Measurement of Blast-Furnace Stockline Contours
by E. W. Voice

Correspondence on Quenched and Tempered Steel

Discussion on Structural Frames for Melting Shops

News and Abstracts

A full list of Contents is given on the Title page (see page 47, Advertisement Section)

WHEEL FORGING

ON A DAVY-UNITED PRESS

THE 6,000 TONS DAVY-UNITED WHEEL FORGING PRESS *at work in the Ickles Works of Steel, Peech & Tozer, Branch of the United Steel Companies Limited. This Press forges railway wheel blanks ready for rolling and dishing from 1,400 lb. cheese ingots in five operations. It was built in the Group's Glasgow Works by Duncan Stewart & Company Limited.*

Photograph by courtesy of Steel, Peech & Tozer

This press, designed for forging solid railway type wheels, has a single main cylinder with a ram 55″ diameter and has a stroke of 4′6″, the column centres being 11′0″ x 5′6″. Hydraulic pressure is supplied from a pump and accumulator service with hydraulic intensifier.

Complete auxiliary gear is incorporated, including a sliding table carrying two anvils for slabbing and finishing respectively, lifting fingers mounted on the crosshead to enable the wheels to be transferred from one anvil to the other, and a swinging arm which carries the slabbing tool and can be brought into use or swung out of the way as required.

DAVY AND UNITED ENGINEERING COMPANY LIMITED, SHEFFIELD

SUBSIDIARIES: DUNCAN STEWART & COMPANY LIMITED, GLASGOW. DAVY AND UNITED ROLL FOUNDRY LIMITED, BILLINGHAM

JOURNAL

of

THE IRON AND STEEL INSTITUTE

Volume 166

1950

SHEFFIELD PUBLIC LIBRARY

Editor
K. HEADLAM-MORLEY

Technical Editor
A. E. CHATTIN, B.Sc.(Hons. Met.) A.R.I.C., F.I.M.

Managing Editor
E. R. MORT, B.Sc., F.I.M.

Assistant Editor
C. R. HARMAN B.Sc.(Eng.)

PUBLISHED AT THE OFFICES OF THE IRON AND STEEL INSTITUTE
4 GROSVENOR GARDENS, LONDON, S.W.1
1950

THE IRON AND STEEL INSTITUTE

4 Grosvenor Gardens, London, S.W.1

❖

COUNCIL AND OFFICERS

as at 1st September, 1950

PRESIDENT

J. R. MENZIES-WILSON, O.B.E.

PAST-PRESIDENTS

Sir Frederick MILLS, Bt.
The Rt. Hon. the Earl of DUDLEY, M.C.
Sir John CRAIG, C.B.E., D.L.
Arthur DORMAN
Cecil H. DESCH, D.Sc., Ph.D., F.R.S.
Sir Andrew McCANCE, D.Sc., F.R.S.

HON. TREASURER

James MITCHELL, C.B.E.

VICE-PRESIDENTS

John Harold ANDREW, D.Sc.
William Beck BAXTER, C.B.E.
Herbert Henry BURTON
Capt. H. Leighton DAVIES, C.B.E.
J. Sinclair KERR, M.Sc.
Gustavus Henry LATHAM
The Hon. R. G. LYTTLETON
Richard MATHER
Gerald STEEL

HON. VICE-PRESIDENTS

Capt. C. A. ABLETT, O.B.E., B.Sc.
The Rt. Hon. Lord AIREDALE OF GLEDHOW, D.S.O., M.C.
Carl A. F. BENEDICKS, Ph.D.
William J. BROOKE
Alfonso de CHURRUCA
Fred CLEMENTS
Wilfred John DAWSON, C.B.E.
Sir John DUNCANSON
Dr. Ing. Robert DURRER
Edmund John FOX
Sir Edward J. GEORGE
Lieut.-Col. Sir John GREENLY, K.C.M.G., C.B.E.
Léon GREINER
J. S. HOLLINGS, C.B.E.
Sir John E. JAMES
Sir William LARKE, K.B.E.
Edward Fulton LAW
Cyril E. LLOYD
Aloyse MEYER
Gunnar SCHJELDERUP
Thomas TURNER, M.Sc.
Sir Arthur B. WINDER

MEMBERS OF COUNCIL

William BARR
Sir Charles BRUCE-GARDNER, Bt.
Donald Fraser CAMPBELL
William Frederick CARTWRIGHT
Ian Frederick Lettsom ELLIOT
Richard Alan HACKING, O.B.E., M.Sc.
John Watson JENKIN, Ph.D., B.Sc.
George Henry JOHNSON
Thomas JOLLY
Sir Arthur MATTHEWS, O.B.E.
Donald Arthur OLIVER, M.Sc.
Neville H. ROLLASON
Frank Henry SANITER
Charles SYKES, D.Sc., Ph.D., F.R.S.
Charles Reginald WHEELER, C.B.E.

HON. MEMBERS OF COUNCIL

Commercial Director, British Iron and Steel Federation .. .. E. W. SENIOR
Director, British Iron and Steel Research Association .. .. Sir Charles F. GOODEVE, O.B.E., D.Sc., F.R.S.
Chairman of the Engineering Committee .. .. C. H. T. WILLIAMS
President of the Cleveland Institution of Engineers .. .. E. T. JUDGE
Chairman of the Ebbw Vale Metallurgical Society .. .. R. C. POWELL, B.Sc.
President of the Institute of Metals .. .. H. S. TASKER
President of the Leeds Metallurgical Society .. .. G. W. GREEN
President of the Lincolnshire Iron and Steel Institute .. .. A. JACKSON
President of the Liverpool Metallurgical Society .. .. S. J. KENNETT, Ph.D.
President of the Manchester Metallurgical Society .. .. E. J. HEELEY
President of the Newport and District Metallurgical Society .. .. G. H. LATHAM
President of the Sheffield Metallurgical Association .. .. J. WHITE, D.Sc.
President of the Sheffield Society of Engineers and Metallurgists .. .. H. W. SWIFT, D.Sc.
President of the Staffordshire Iron and Steel Institute .. .. E. MARKS, Ph.D
President of the Swansea and District Metallurgical Society .. .. H. J. THOMAS
President of the West of Scotland Iron and Steel Institute .. .. W. BARR
Representatives of the Institution of Metallurgists .. .. W. E. BARDGETT, B.Sc.
W. W. STEVENSON

SECRETARY

K. HEADLAM-MORLEY

ASSISTANT SECRETARY

A. E. CHATTIN, B.Sc.(Hons. Met.)

LIBRARIAN

R. ELSDON

CONTENTS

VOLUME 166 **1950**

DISCUSSION AND CORRESPONDENCE ON PAPERS

PAGE

" Electron Microscope Study of Quenched and Tempered Steel," by J. Trotter and D. McLean ... 17

" Open-Hearth Furnace Models," by J. H. Chesters, A. R. Philip, R. S. Howes, and I. M. D. Halliday, " Experiments on Gaseous Mixing in Open-Hearth Furnace Models," by R. D. Collins and Miss J. D. Tyler, and " Experiments on the Gas and Fluid Flow in a Side-Blown Converter Model " by M. P. Newby 186

" Mechanical Properties of Low-Carbon, Low-Alloy Steels Containing Boron," by W. E. Bardgett and L. Reeve 193

" Further X-Ray Study of the Equilibrium Diagram of the Fe–Ni System," by E. A. Owen and Y. H. Liu, " Free-Energy and Metastable States in the Fe–Ni and Fe–Mn Systems," by F. W. Jones and W. I. Pumphrey, " Microscopical Studies on the Iron–Nickel–Aluminium System, Part I—$\alpha + \beta$ Alloys and Isothermal Sections of the Phase Equilibrium Diagram," by A. J. Bradley, and " Constitution of Iron–Nickel–Chromium Alloys at 650° to 800° C.," by W. P. Rees, B. D. Burns, and A. J. Cook 200

" The Compression Test in Relation to Cold Rolling," by N. H. Polakowski 305

" Distribution of Materials in the Blast-Furnace, Part II—Compensated Charging," by H. L. Saunders and R. Wild, " Investigations on an Experimental Blast-Furnace," by H. L. Saunders, G. B. Butler and J. M. Tweedy, and " A Radio-Active Technique for Determining Gas Transit Times in a Driving Blast-Furnace," by E. W. Voice 315

" Plastic Strain and Hysteresis in Drawn Steel Wire," by R. S. Brown 319

" The Effect of Sodium Oxide Additions to Steelmaking Slags : Part I—Use of Soda to Dephosphorize Pig Iron at 1400° C.," by W. R. Maddocks and E. T. Turkdogan 320

" Change of Electrical Resistance During Strain-Ageing of Iron," by A. H. Cottrell and A. T. Churchman 322

IRON AND STEEL INSTITUTE PAPERS

PAGE

"Penetration of Molten Metal into Compacted Sand," by T. P. Hoar and D. V. Atterton 1

"The Distribution of Temperature in Ingot Moulds and Its Relation to Ingot Structure," by I. M. Mackenzie and A. Donald 19

"The Production of Steel Plates in Scotland," by J. A. Kilby 29

"Effect of Cooling Rate and Composition on the Embrittlement of Weld Metal," by E. C. Rollason and R. R. Roberts 105

"The Accurate Determination of Carbon in Low-Carbon Steels," by J. E. Wells 113

"Rapid Estimation of Phosphorus in Steels," by A. Hans 118

"Ionic Theory of Slag–Metal Equilibria : Part I—Derivation of the Fundamental Relationships," by P. Herasymenko and G. E. Speight 169

Historical Note No. 24—"The Truth about Dud Dudley," by H. R. Schubert 184

"Spectrochemical Analysis of Steelmaking Slags," by C. G. Carlsson and J. T. M. Yü 273

"The Transformations α–γ and γ–α in Iron-Rich Binary Iron–Nickel Alloys," by N. P. Allen and C. C. Earley 281

"Ionic Theory of Slag–Metal Equilibria : Part II—Applications to the Basic Open-Hearth Process," by P. Herasymenko and G. E. Speight 289

"A Note on Silicon Distribution between Austenite and Liquid Metal in Freezing Hypo-Eutectic Cast Iron," by A. Hultgren and O. Carlsson 303

BRITISH IRON AND STEEL RESEARCH ASSOCIATION

"Ingot Heat Conservation : Some Methods of Calculating Internal Temperatures from Surface Temperatures of Ingots," by the Fuel Research Committee 71

"Use of Aluminium in Hot-Dip Galvanizing," by M. L. Hughes 77

"The Measurement of Stockline Contours on Driving Blast-Furnaces," by E. W. Voice 84

"Corrosion of Bare Iron or Steel in Sea Water," by J. C. Hudson 123

"The Thermodynamic Background of Iron and Steelmaking Processes. II—Deoxidation," by F. D. Richardson 137

"Continuous Temperature Measurement of Liquid Steel in the Furnace," by D. Hardwick and H. Everard 147

PAGE

"The Thermodynamics of Substances of Interest in Iron and Steel Making: II—Compounds between Oxides," by F. D. Richardson, J. H. E. Jeffes, and G. Withers 213

"Experiments on Gaseous Mixing in Open-Hearth Furnace Models," by R. D. Collins and J. D. Tyler 235

"Contribution of the Source Unit to Variability in Spectrographic Analysis," by the Spectrographic Analysis Sub-Committee 325

"A Statistical Study of the Behaviour of Spectrographic Source Units," by H. T. Shirley, A. Oldfield and H. Kitchen 329

"Distribution of Materials in the Blast-Furnace: Part III—Further Factors Influencing the Distribution of Solids in the Blast-Furnace," by R. Wild 339

IRON AND STEEL WORKS ENGINEERING

Report of the Twelfth Meeting (Morning Session):

Joint Discussion—"Traffic of Iron and Steel Works—A Method of Traffic Analysis," by H. H. Mardon and M. D. Brisby and "Traffic of Iron and Steel Works—The Application of Very High-Frequency Radio Communication" 349

Report of the Twelfth Meeting (Afternoon Session):

General Discussion—"Structural Frames for Melting Shops," by J. S. Terrington 85

and "A Proposed Method of Specifying Travel-Motion Performance for Steelworks Overhead Cranes," by D. A. Wise and L. N. Bramley 246

News 89, 149, 253, 356

Translations 92, 153, 256, 360

Abstracts 93, 154, 257, 361

Book Notices 101, 166, 271, 391

New Publications 103, 168, 272, 392

ABBREVIATIONS AND SYMBOLS

Å.	Ångstrom unit(s) = 1×10^{-10} m.
A.C.	air-cooled ; alternating current
A.H.	air-hardened
amp.	ampère(s)
amp.hr.	ampère-hour(s)
approx.	approximately
at.-%	atomic per cent
at.wt.	atomic weight
atm.	atmosphere(s) (pressure)
A.W.G.	American wire-gauge
° Bé.	Baumé (degree)
b.h.p.	brake horse-power
B. & S.	Brown and Sharpe (gauge)
B.o.T.	Board of Trade
b.p.	boiling point
B.T.U.	Board of Trade unit(s)
B.Th.U.	British thermal unit(s)
B.W.G.	Birmingham wire-gauge
° C.	centigrade; Celsius (degree)
cal.	calorie(s)
c.c.	cubic centimetre(s)
c.d.	current density
c.g.s.	centimetre-gramme-second unit(s)
cm.	centimetre(s)
coeff.	coefficient(s)
conc.	concentrated
const.	constant(s)
cu.	cubic
cwt.	hundredweight(s)
D.C.	direct current
dia.	diameter
dil.	dilute
dm.	decimetre(s)
e.m.f.	electromotive force
e.v.	electron volt(s)
° F.	Fahrenheit (degree)
ft.	foot, feet
ft.lb.	foot-pound(s)
g.	gramme(s)
gal.	gallon(s)
H.F.	high-frequency
h.p.	horse-power
h.p.hr.	horse-power-hour(s)
hr.	hour(s)
in.	inch(es)
in.lb.	inch-pound(s)
I.S.W.G.	Imperial standard wire-gauge
° K.	absolute temperature (Kelvin scale)
kg.	kilogramme(s)
kg.cal.	kilogramme-calorie(s)
kg.m.	kilogramme-metre(s)
km.	kilometre(s)
kV.	kilovolt(s)
kVA.	kilovolt-ampère(s)
kW.	kilowatt(s)
kWh.	kilowatt-hour(s)
kX.	crystal Ångstrom(s) = 1000 Siegbahn X-units

l.	litre(s)
lb.	pound(s)
L.F.	low-frequency
M	molar (solution)
m.	metre(s)
m.amp.	milliampère(s)
max.	maximum
mg.	milligramme(s)
min.	minimum ; minute(s)
ml.	millilitre(s)
mm.	millimetre(s)
m.m.f.	magnetomotive force
m.p.	melting point
mV.	millivolt(s)
mμ	millimicron = 1×10^{-9} m. = 10 Å.
N	normal (solution)
N.T.P.	normal temperature and pressure
O.H.	open-hearth ; oil-hardened
O.Q.	oil-quenched
oz.	ounce(s)
p.d.	potential difference
*p*H	hydrogen-ion concentration
p.p.m.	parts per million
r.p.m.	revolutions per minute
sec.	second(s)
sp.gr.	specific gravity
sq.	square
S.W.G.	standard wire-gauge
T.	tempered
temp.	temperature
V.	volt(s)
VA.	volt-ampère(s)
W.	watt(s)
Wh.	watt-hour(s)
W.G.	water-gauge
W.Q.	water-quenched
wt.	weight
wt.-%	weight per cent
yd.	yard(s)
μ	micron(s) = 1×10^{-6} m.
μg	microgramme(s) = 1×10^{-6} g.
μμ	1 millionth micron = 1×10^{-12} m. = 0·01 Å.
Ω	ohm(s)
°	degree (arc or temperature)
′	minute of arc ; foot (feet)
″	second of arc ; inch(es)
$<$	less than
$>$	greater than
$\not<$	not less than
$\not>$	not greater than
$\leqslant$	equal to or less than
$\geqslant$	equal to or greater than
$\neq$	not equal to
$\equiv$	identically equal to
$\simeq$	approximately equal to
$\propto$	proportional to

Unless otherwise stated above, the symbols given in the following British Standards are used in the *Journal*: Chemical, Thermodynamical, and Physico-chemical quantities: B.S. 813; Engineering units: B.S. 560.

W. E. BARDGETT, B.Sc., A.M.I.Mech.E., F.I.M.

WILLIAM EDWARD BARDGETT was born and educated in Glasgow. He left school in 1915 to join the Army, later transferring to the Royal Flying Corps in which he served as a Lieutenant-Pilot until 1919. He received his technical education at the Royal Technical College, Glasgow, and obtained the B.Sc. degree of London University in 1928.

After a period on the chemical laboratory staff of Messrs. Colvilles Limited, Mr. Bardgett transferred to the Metallurgical Department, where he was concerned mainly with works heat-treatment problems. Later, he turned to research, and gave much time to the study of creep of metals, including the development of the Barr-Bardgett short-time creep test method.

In 1933 Mr. Bardgett joined the staff of the Central Research Department, The United Steel Companies, Limited, in charge of the Metallurgical Section, under the late Dr. T. Swinden. In 1945 he was appointed to his present position of Research Manager, following the appointment of Mr. F. H. Saniter as Director of Research of the newly-constituted Research and Development Department.

During his association with The United Steel Companies, Limited, Mr. Bardgett's activities have covered a wide range of metallurgical subjects dealing with most classes of steels. He has contributed articles and papers on the subjects of lead in steel, fatigue, creep, strain-age embrittlement, hardenability, cold rolls, spring steels, and low-carbon low-alloy steels containing boron.

Mr. Bardgett is a member of several British Standards Institution Committees, and is a British delegate to the International Standards Organisation Technical Committee 17, dealing with steel testing. He is also a member of several British Iron and Steel Research Association Committees, including the Metallurgy (General) Divisional Panel, Alloy Steels Research Committee, Inclusions Sub-Committee, and the Sheet-Metal Working Committee, of which he is Chairman.

Mr. Bardgett has also served on the Thermal Treatment and Hair-Line Crack Sub-Committees. He has for many years been a member of the British Electrical and Allied Industries Research Association J/E Committee, is Chairman of the J/Eb Panel dealing with cracking in steam pipes, and is a member of the Ferrous Metals Committee of the Inter-Service Metallurgical Research Council.

Mr. Bardgett joined The Iron and Steel Institute in 1933, and is an Honorary Member of Council representing the Institution of Metallurgists. He is a Past-President of the Sheffield Metallurigcal Association, of which he is a James Taylor Prize winner, and is an Associate Member of the Institution of Mechanical Engineers.

Havana Vandyk

W. E. Bardgett, B.Sc., A.M.I.Mech.E., F.I.M.
Honorary Member of Council

IRON AND STEEL
INSTITUTE PAPERS

PLANT DESIGN · MANUFACTURE · RESEARCH · DEVELOPMENT

Penetration of Molten Metal into Compacted Sand

By T. P. Hoar, M.A., Ph.D., B.Sc., and D. V. Atterton, B.A.

SYNOPSIS

The factors influencing metal penetration into compacted sand, with special reference to high-temperature ferrous castings in sand moulds, have been investigated by means of a flexible laboratory apparatus capable of simulating practical conditons of temperature, pressure, metal movement, surface treatment of the mould, and chemical reaction between metal and mould.

It is shown that molten iron, steel, and a number of non-ferrous metals do not wet silica, and that consequently a critical metallostatic pressure, termed the ' penetrating pressure,' must be reached at the metal/sand-compact interface before penetration can occur. For iron and steel at about 1600° C. in contact with sand compacts of average mesh, the penetrating pressure is of the order of 20–60 cm. of Hg, or 35–110 cm. of iron or steel.

Penetrating pressure is proportional to the metal surface tension, and increases with decrease of sand grain size, since this causes a decrease of effective pore radius. The penetrating pressures for iron and steel are reduced by the sand sintering that occurs at steel casting temperatures, since this tends to increase the effective pore radius, but they would be increased at still higher temperatures where the extensive fusion can close pores. For sand compacts of the same grain-size distribution, differing only in binder content, the penetrating pressure of iron at 1600° C. is nearly proportional to the air-permeability time at 20° C., both properties showing a maximum at an optimum binder content.

The penetrating pressure for iron increases with increasing surface oxidation for metal, owing to the formation of ferrous silicates which partially plug the pores in the sand compact. There is evidence that, under non-oxidizing conditions, the penetrating pressure decreases with increase of carbon content in steel.

Silica mould washes do not greatly influence the penetrating pressure of iron, owing to cracking, but they tend to reduce sand adherence, by localizing the points of penetration. Thick washes so compounded that they melt to slag-like materials can, by filling pores and covering the sand surface with a continuous viscous layer, prevent metal penetration and sand adherence.

Calculations of the rate and extent of penetration, based on known values of metal and slag viscosities and on extrapolated values of the thermal conductivities of compacted sands, show that penetration of either metal or slag occurs in a fraction of a second to the depth of sand heated to the solidification temperature of the penetrating fluid. The depth of penetration is limited by the thermal diffusivity of the sand compact and by the degree of superheat of the penetrating fluid, not by its viscosity.

Introduction

THIS paper describes an investigation of certain physical and chemical actions that occur between molten metals, particularly iron and steel, and sand moulds. The work arose out of a discussion between Mr. A. B. Lloyd, of F. H. Lloyd and Co., Ltd., and one of the authors (T.P.H.), on the problem of metal penetration and sand ' burn-on ' in steel castings. It was thought that an investigation of the fundamental physics and chemistry of the processes that occur at the interface of molten metal and compacted sand would give results that, while of interest in themselves, might point the way towards improvements in practice.

Certain aspects of the problem of mould/metal actions are being investigated by the Mould Surface Committee of the American Foundrymen's Association, which is concerned at the moment with the chemistry of liquid steel in contact with sand.[1] This work has already ruled out the possibilities that oxidation of metal and its subsequent reduction,[2, 3] or metal volatilization,[4] play any part in the mechanism of penetration.

Caine[5] extensively investigated the problem of ' burn-on ' or adhering sand ; his conclusions may be summarized as follows :

(1) Adhering sand is the result of metal penetration into large voids in the sand, which mechanically locks the sand to the metal.

(2) Voids may arise either through the use of sand of large grain size, or through the fusion of colloidal matter and finer silica particles present in the sand.

(3) Metal will penetrate either type of void, provided that the sand temperature is higher than the melting point of the steel.

Manuscript received 21st November, 1949.

Dr. Hoar is Lecturer in Metallurgy, and Mr. Atterton is in the Department of Metallurgy, at Cambridge University.

(4) Metal penetration may be prevented or reduced by (i) the formation of a continuous viscous fused film, such as that produced when molten metal strikes a properly applied silica wash, or (ii) the setting up of a gas pressure, as, for instance, when metal heats an organic binder incorporated in the sand mix.

Ljunggren[6] carried out an investigation of the influence of numerous variables on sand adherence, finding a definite correlation between adherence on the one hand, and permeability, mean grain size, and sintering point on the other, an increase of adherence corresponding to an increase of each of these three properties. Ljunggren mentions that knowledge of the chemical reactions that take place at the zone of contact between mould and metal is small, but suggests that the penetration of the steel may be prevented by impervious layers of slag formed at the metal/mould interface ; this is supported by the microscopic investigations of Holmquist.[6] Ljunggren's hypothesis also receives support from Vaska,[7] who points out that contact with metallic oxides greatly reduces the fusion temperatures of moulding materials. He believes that penetration is prevented when the surface of the mould is melted by reaction with any metallic oxides present to form an impervious layer of viscous slag, and suggests that this layer, on cooling, leaves the surface of steel cleanly because of the difference between the coefficients of expansion. If, on the other hand, there is no fused layer, it is quite likely that the non-viscous steel will penetrate between the sand grains, resulting in adherence of the moulding material to the casting. Similar opinions have been expressed by Wagner,[8] commenting on the work of Ardenne and Endell.[8]

Bachelor[9] considers that the penetration of an alloy grey iron into the link cores in the throws of a crankshaft is caused by the forcing apart of the sand grains by expansion, and by deposition of carbon from hydrocarbon gases produced from organic binders. The admixture of 2% iron oxide with the core sand was found to solve the problem, although the mechanism of its action is not entirely clear.

The above papers are concerned almost entirely with practical observations of penetration into moulds and of the resulting sand adherence ; although the authors have advanced various hypotheses for the mechanism of penetration and the factors influencing its extent, they have not attempted experimental verification of their ideas.

Scope of Present Investigation

Examination of specimens of penetrated sands has revealed the qualitative information, much of it novel, described in the next section, but leads to little further fundamental understanding of the problem than is implicit in the previous hypotheses.

The following factors, which may decide whether metal penetrates a sand mould and the depth to which it penetrates, have therefore been considered and in most cases investigated experimentally:

(i) surface tension of the molten metal
(ii) contact angle of the metal with the sand, and its modification by chemical reactions
(iii) pressure across the metal/mould interface
(iv) effective pore radius of the sand, and its modification by sand composition, particle size, expansion of the sand, fusion, etc.
(v) formation of slag barrier layers
(vi) presence and properties of mould washes
(vii) viscosity of the metal
(viii) thermal properties of the sand, pouring temperature of the metal, and rate of cooling of the molten metal, these factors determining the depth of facing sand that is heated to above the melting point of the metal.

The main experimental results have been obtained by investigating the reactions between small laboratory melts of metal and sand compacts, using the apparatus described on page 4. This apparatus allows a variety of atmospheres, and pressures across the metal/mould interface, to be used. Theoretical treatments of the depth of penetration, and the influence of metal viscosity and of pouring rate on penetration, are given later in the paper.

EXAMINATION OF SPECIMENS COLLECTED FROM INDUSTRIAL CASTINGS

An examination of penetrated sands from commercial castings was made, using microscopic, chemical, petrographic, and X-ray methods, to obtain general information on the mechanism of penetration and to compare facing sands giving a clean peel with those showing varying degrees of adherence. Several specimens, of three main types, were removed from the surface of castings : (*a*) completely penetrated sand, (*b*) moderately penetrated sand, and (*c*) penetrated sand giving a clean peel.

The following observations were made :

(a) *Completely Penetrated Sand*—A large piece of completely penetrated sand, prised with difficulty from a re-entrant angle in a large casting,[10] was examined. A small piece of the very hard and abrasive material was mounted in plastic moulding powder and cross-sectioned with an alundum cutting wheel. Microscopic examination revealed several interesting results. Figure 5*a* shows the unetched structure of sand and metal. Figures 5*b* and *c* show the specimen etched with 2% nital ; considerable decarburization has occurred and the remaining carbon is in the form of coarse pearlite segregated at the metal/sand-grain interface. The decarburization is caused by reaction of the steel with oxygen in the sand pores, and perhaps also with silica, as discussed later. The segregation has occurred because the very slow cooling has led to the crystallization of primary ferrite in the body of the probe, which in this case has cooled before the layer of metal at the sand-grain interface. This effect must often occur in re-entrants (and always in cores), where the direction of heat flow during cooling is from any penetrated sand to the casting ; but the reverse segregation is to be expected near the ends of metal probes in penetrated sand on the outside of a casting, where the heat flow is outwards through the mould (*see* c).

(b) *Moderately Penetrated Sand*—The specimen was mounted in moulding material and prepared for micro-examination. Figure 6 shows the unetched structure ; a definite material other than sand and metal, probably (in the light of further work (*see* c)) slag, is visible.

(c) *Penetrated Sands Giving a Clean Peel*—These specimens, from the outer parts of a casting, were of great interest in showing that penetration need not necessarily lead to ' burnt-on ' sand. Figure 7*a* shows

Table I

ANALYSES OF METALS

	C, %	Mn, %	Si, %	S, %	P, %	Ni, %	Cr, %
Armco Iron	0·012	0·07	0·017	0·017	0·005		
Steel H4183 (Al killed)*	0·30	1·14	0·36	0·019	0·019	0·14	0·09
Steel H4173 (Al killed)*	0·27	1·27	0·45	0·018	0·016	0·18	0·05
Steel En 9	0·55	0·55	0·35	0·06	0·06		

Lead	99·93%	Source unknown
Tin	99·89%	Chempur
Copper	99·99%	O.F.H.C.
Mercury		Pure redistilled
Antimony	99·92%	Johnson Matthey

*Steels H4183 and H4173 supplied by William Jessop & Sons, Ltd.

the unetched structure of metal and sand, and also a phase similar to that noted in Fig. 6 but found at the peeling surface. The etched structure (Fig. 7*b*) shows considerable decarburization, and very coarse pearlite such as would result from the very slow cooling that occurs in large castings. There is a tendency for ferrite to be localized at the metal/sand-grain interface ; this might be expected, since the heat flow is here outwards through the mould (*see* a).

The top layer of the sand (down to a depth of 0·25 cm.) was ground to about 250 mesh in an agate mortar, and an X-ray powder photograph was taken, using copper Kα radiation. A strip of nickel foil was placed in front of the film to absorb fluorescent radiation from the iron. The following substances were indicated by the complex photograph obtained :

α-quartz	conclusive
Cristobalite	conclusive
Magnetite	strong indication
Fayalite	strong indication
Mullite	slight indication

The possible presence of mullite is explained by the fact that bentonite, used as binder in the sand mix, decomposes to mullite at high temperatures.[11]

A specimen of the facing sand was ground to a very thin section, which was petrographically examined in transmitted light (Fig. 8) and plane-polarized light. Two finely divided iron silicates, fayalite ($2FeO.SiO_2$) and clinoferrosilite ($FeSiO_3$) were detected at the interface between sand grains and metal, the fayalite occurring nearer the iron and the clinoferrosilite nearer the sand grains. The clinoferrosilite was not of high purity, being contaminated with about 1% of both calcium and magnesium metasilicates ; these impurities no doubt arise from the bentonite binder in the sand mix.

The most important result of the above examination of penetrated sands in commercial castings is the demonstration of the presence of slag materials at and near the metal/mould interface. Several of the effects produced on metal penetration by this slag formation, and by the other factors listed on page 2, have been investigated by the experimental methods described below.

MATERIALS

Metals

The analyses of the metals used for penetrating experiments are given in Table I.

Before use, all metals were melted in silica crucibles to give sound pellets of each metal. Lead, tin, and antimony were melted with free access to air. The Armco iron and copper were melted in the high-frequency furnace under an air pressure of 10^{-3} cm. of Hg. Steels were melted under a pressure of about 70 cm. of argon ; relatively sound ingots were obtained which were perfectly satisfactory for experimental purposes, although melting steels under argon at pressures from 10^{-3} cm. to 10 cm. produced heavily gassed thimbles of metal. Chemical analysis supports the view that this is caused by reduction of the silica of the crucible by the carbon in the steel.

Additional metals used for optical pyrometer calibration were : 99·97% nickel ;* 99·9% manganese.†

Sands

The sands used were of two classes :

(1) Commercial foundry sands, supplied by F. H. Lloyd and Co., Ltd. (*see* Table II).

* Mond Nickel Co. † Everett, Liverpool.

Table II

COMMERCIAL FOUNDRY SAND MIXES

Sand Mix	Composition, wt. %						Physical Properties of Sand Compacts					
	Leighton Buzzard		Silica Flour	Bentonite	Kordek	Water	Green			Dry		
	Fine Silica	Coarse Silica					Standard Rams	Perm. No.*	Density	Standard Rams	Perm. No.*	Density
F1	36·2	60·5	...	2·4	0·9	4·2	3 6	100 63	1·670	3 6	140 110	1·600
F3	43·5	42·0	11·2	2·4	0·9	6·6	3 6	38 25	1·831	3 6	66 43	1·721
F4/A	43·5	36·4	16·8	2·4	0·9	7·6	3 6	19 11	1·996	3 6	34 27	1·818

* The permeability number P of a sand compact is defined by the formula $P = \frac{Vh}{pat}$, where V ml. is the volume of air passed in time t sec. through a compact h cm. high and a sq. cm. cross-sectional area, by a pressure p cm. of water.

Table III

LABORATORY PREPARED SAND MIXES

Sand Mix	Composition, wt. %			
	B.D.H. Sand		Bentonite	Water
	30–40 mesh	60–80 mesh		
A	56·0	36·0	4·0	4·0
B	56·5	36·5	3·0	4·0
C	56·75	36·75	2·5	4·0
D	57·0	37·0	2·0	4·0
E	57·25	37·25	1·5	4·0
F	57·5	37·5	1·0	4·0

(2) Simple sand mixes, consisting of washed B.D.H. silica sand, Wyoming bentonite and water (*see* Table III).

The following technique was employed for preparing the sand mixes :

Two sieve fractions, 30–40 and 60–80 mesh, of the silica sand were placed in a screw-top bottle and mixed in a rotator (60 r.p.m.) for five minutes, after which the desired percentage of water was added, and then the bentonite. The mixture was shaken in an electrical shaker for twenty minutes ; a certain amount of lumping took place during this treatment, so the sand was passed through a coarse sieve in order to break up the aggregates into their constituent sand grains. This technique is a departure from normal foundry practice ; however, it achieves the primary function of milling by coating each sand grain uniformly with clay, and has the added advantage of leaving the grain size substantially unaltered. The compacts made from the sand mixes are reproducible with regard to both air-permeability and penetrating pressure (*see* page 7).

Washes

The ingredients of laboratory prepared washes (Table IV) were ground separately to about 250–300 mesh in a tungsten carbide ball crusher. The dry ingredients were placed in a bottle and mixed in a rotator (60 r.p.m.) for half an hour. Water was then added until the desired fluidity was obtained.

APPARATUS AND TECHNIQUE

Requirements of the Apparatus

An apparatus used for investigating the reactions that occur at the metal/mould interface should reproduce the following conditions :

(i) The sand should be heated by contact with the molten metal.
(ii) The metal should be in motion.
Conditions (i) and (ii) can be satisfied by using high-frequency induction heating.
(iii) The pressure of the molten metal should be of the same order as that in typical commercial ferrous castings, where the height of molten metal ranges from a few centimetres to more than a hundred.

In preliminary experiments with low ferrostatic pressures (about 2 cm. of molten iron at the metal/sand interface) no penetration occurred. It was found in later experiments that there is a critical pressure, for any given sand compact and metal at a particular temperature, at which the metal crosses the macroscopic metal/sand interface and penetrates into the larger pores of the sand ; this pressure has been termed the ' penetrating pressure.'

Design

The apparatus (Fig. 1) consists of a high-frequency induction furnace suitable for melting small amounts of metal on top of beds of sand, under vacuum. The high-frequency current is obtained from a 35-kVA. spark-gap generator. The vacuum pump is a Cenco Hyvac capable of reaching a pressure of 4×10^{-5} cm. of Hg ; a typical pumping curve for the apparatus is given in Fig. 2. Gas pressure, up to atmospheric, may be applied to the upper surface of the molten metal ; one atmosphere is approximately equivalent to 1·3 m. of molten iron or steel, and thus pressure conditions corresponding to a wide range of casting size can be obtained. The gas normally used is argon, from which traces of oxygen and moisture are removed by passing it through potassium hydroxide pellets, concentrated sulphuric acid, phosphorus pentoxide, and copper, nickel, and iron gauzes, these metals being heated to about 750° C. If desired, experiments may be carried out under controlled pressures of oxygen, inert atmospheres, or any other gas.

The temperature of the molten metal is measured

Table IV

WASH COMPOSITIONS

No.	Designation	Composition, wt. %
1	Lloyd's Silica Wash	39·1% silica flour, 2% bentonite, 2·2% organic binder,* 56·7% water
2	FeO composition wash	63% ' FeO,'† 2% bentonite, 35% water
3	Fayalite composition wash, A	14% SiO_2, 32·5% FeO, 2% bentonite, 51·5% water
4	Fayalite composition wash, B	17% SiO_2, 40% FeO, 2% bentonite, 41% water
5	Fayalite composition wash, C	21% SiO_2, 49% FeO, 2% bentonite, 28% water
6	Fayalite wash	63% fayalite,‡ 2% bentonite, 35% water
7	Silica-rich iron silicate wash	63% slag,§ 2% bentonite, 35% water
8	Magnetite wash	63% Fe_3O_4, 2% bentonite, 35% water
9	Lime wash	32% CaO, 2% bentonite, 66% water
10	Lime–silica wash, A	25% CaO, 25% SiO_2, 2% bentonite, 48% water
11	Lime–silica wash, B	13·7% CaO, 24·3% SiO_2, 2% bentonite, 60% water
12	Lime–silica wash, C	13% CaO, 27·8% SiO_2, 2% bentonite, 57·2% water
13	Alumina–silica wash	4·5% Al_2O_3, 40·5% SiO_2 2% bentonite, 53% water

* A proprietary core binder, consisting of about ⅓ linseed oil, ⅓ dextrine, ⅓ water.
† Prepared by heating iron oxalate at 1100° C. in a tube sealed with a bunsen valve.
‡ Prepared by melting ' FeO ' and silica together in the H.F. furnace.
§ Prepared by grinding up a silica crucible that had been in contact with molten FeO.

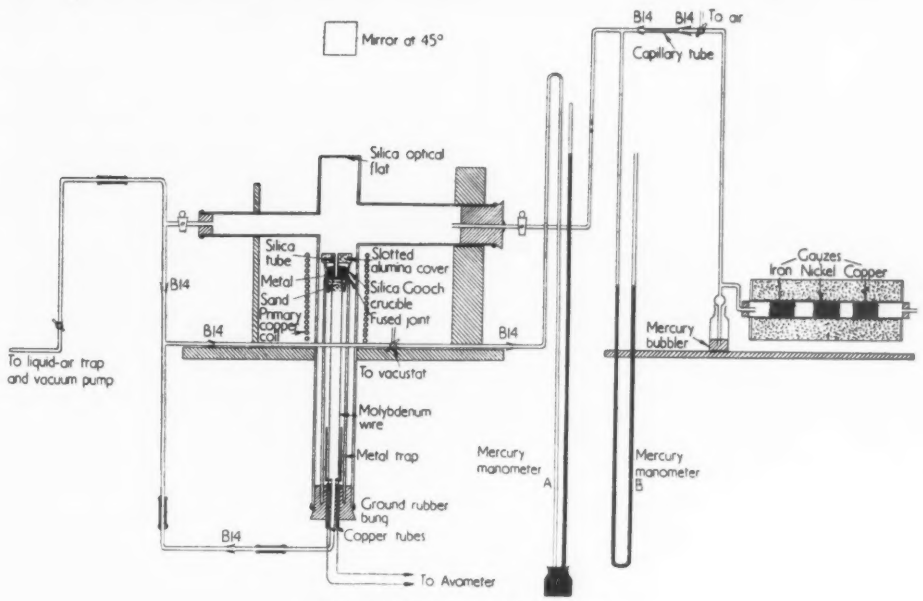


Fig. 1—Diagram of apparatus

with a disappearing-filament pyrometer by observing a sighting tube of silica, partially immersed in the molten metal, through a silica optical flat ; the length/diameter ratio for the immersed part of the tube is sufficient to give black-body radiation. The disappearing-filament pyrometer was calibrated by taking cooling curves of pure metals. The melting points of the metals used were : iron, $1539 \pm 3°$ C. ; nickel, $1455 \pm 1°$ C. ; manganese, $1245 \pm 10°$ C. ; copper, $1083 \pm 0{\cdot}1°$ C.[12] A marked arrest corresponding to the melting point was obtained in each case ; the calibration curve, apparent temperature against true temperature, is rectilinear (Fig. 3). Temperatures can be measured to an accuracy of at least $\pm 5°$ C., and the high-frequency furnace can be controlled so that the temperature does not vary by more than $\pm 10°$ C. over a period of a few minutes.

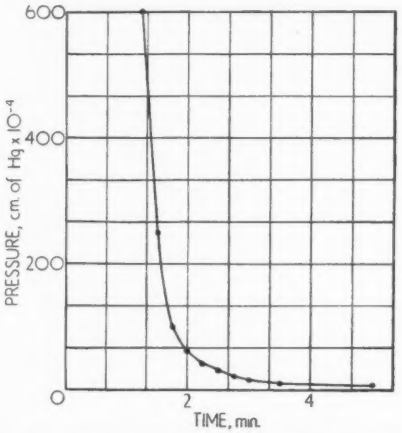


Fig. 2—Typical pumping curve for apparatus

Ramming of the Sand

The sand was placed in the silica Gooch crucible and rammed hard in a qualitatively reproducible way to a constant height of 2·2 cm. The correct volume of sand for a sand compact of this height could usually be estimated, but if the height turned out to be either too large or too small the compact was broken up and sand either removed or added, until, on re-ramming, the compact was of the standard height. This technique gives reproducible air-permeability and penetrating pressure values for the compact.

Permeability of the Sand

The permeability of the sand compact *in situ* in the crucible was measured by means of a standard B.C.I.R.A. apparatus, and the time taken for 2 l. of air to pass through the compact was measured. These times cannot be converted to permeability numbers (*see* Table II, footnote) because the mesh of the Gooch crucible determines the apparent area of the

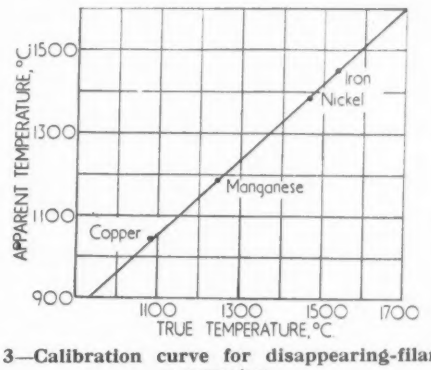


Fig. 3—Calibration curve for disappearing-filament pyrometer

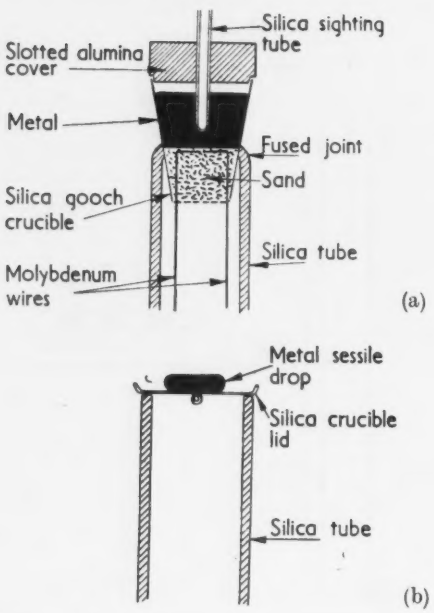


Fig. 4—Details of apparatus: (*a*) for penetrating pressure experiments, (*b*) for sessile drop experiments

compact. However, since sand compacts of constant height and a constant volume of gas were employed throughout the experiments, the permeability times are a satisfactory arbitrary measure of the permeabilities of the sands.

Determination of Penetrating Pressure

While the sand was being rammed in the Gooch crucible as described, the ends of two insulated molybdenum wires were embedded in the sand, as shown in Figs. 1 and 4*a*, so that they were about 1 mm. below the final surface of the compact. The other ends of the wires were connected to an ohmmeter. When metal penetration of the sand occurs this simple circuit is completed by a low resistance, and the penetration is indicated by the ohmmeter. A specimen of degassed metal, with a hole drilled down its centre fitted with the silica sighting tube, was placed on top of the sand. The apparatus was then assembled and the system was pumped down to a pressure of 10^{-3} cm. of Hg or less. Next the power was switched on to the furnace ; in the majority of experiments the specimen was taken up to temperature in about 2 min. and held at temperature for 0·5 min. Argon was then admitted to the system through a very fine capillary, so that the rate of increase of pressure on the upper surface of the metal was quite slow, between 1 and 1·5 cm. of Hg per sec. When the ohmmeter indicated penetration, an instantaneous photograph was taken of manometer *B* (Fig. 1) ; this photographic technique minimizes any delay between observing penetration and reading the steadily falling mercury manometer. The penetrating pressure is calculated from the observed manometer reading and the measured height of metal in the crucible.

Micro- and Macro-Examination of Specimens

After cooling for 3–4 hr., specimens were mounted in Diakon moulding material, with a special die and heater prepared for the purpose ; this mounting preserves the adhering sand and facilitates the cross-sectioning of the specimen, carried out with an alundum cutting wheel. Figures 9 and 10 are representative micro- and macro-photographs of a specimen, taken using vertical illumination, showing metal, sand, and voids ; comparison of Fig. 10 with Fig. 5*a* shows the similarity between the experimentally produced penetration and that found in practice.

Apparatus for Sessile Drop Experiments

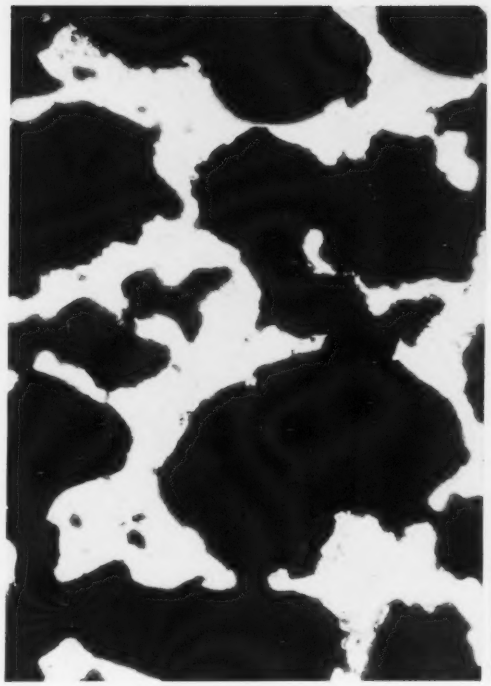
This consists of a silica crucible lid placed on top of a silica tube (Fig. 4*b*). The specimen of metal, approximately 10 g., was placed on the crucible lid and heated *in vacuo* to about 100° C. below the melting point of the metal. Argon was then admitted up to a pressure of about 70 cm. of Hg. The specimen was melted and kept molten for approximately 5 minutes ; the H.F. current was then switched off, so that the specimen solidified without being distorted by eddy currents.

RESULTS AND INTERPRETATION

Non-Wetting of Silica by Molten Metals

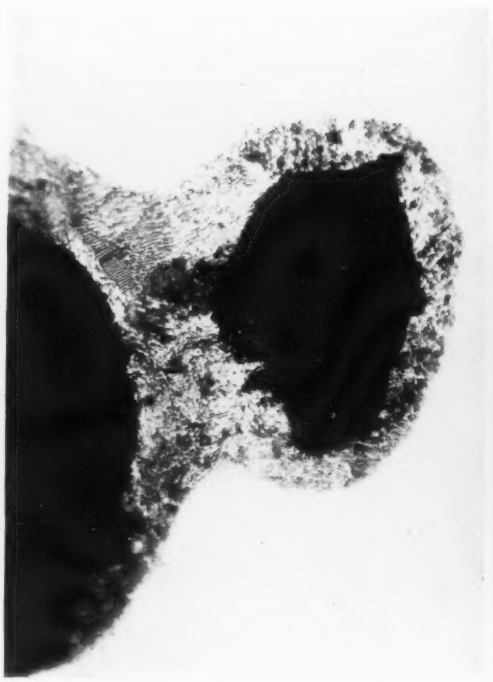
When small pellets of Armco iron, about 2 cm. high, were melted in contact with beds of sand in air at 10^{-3} cm. of Hg, and also at atmospheric pressure, no penetration occurred, except in the case of a coarse 10–20 mesh sand. This indicates that wetting of silica by the metal does not occur, as might be inferred from the fact that a drop of mercury does not penetrate into compacted sand. It has, moreover, been conclusively demonstrated by qualitative sessile drop experiments. Small 10-g. pellets of Armco iron, lead, tin, and copper were melted on a fused silica crucible lid under a pressure of about 70 cm. of argon. Visual observation at temperature and after cooling indicated no spreading of metal over the silica surface in any instance ; Figs. 11*a* and *b* show the results obtained with tin and Armco iron respectively, and Fig. 12 shows a vertical cross section of the tin drop with a contact angle of approximately 130°. Accurate contact-angle and surface-tension measurements on these drops are not possible, because the silica surface is not plane and because of the contraction of the drop on cooling. When a similar pellet of Armco iron was melted on the silica surface with free access of air, spreading of iron oxide occurred (Fig. 11*c*) and examination of the layer between the oxide and silica revealed the presence of yellowish-grey iron silicate ; however, the metal did not spread on the oxide—it will be recalled that mercury does not spread on surfaces of metals covered with an oxide film.

These results show that molten metals do not spread on silica, with which they make large contact angles. Thus, penetration of metal into sand moulds must be a consequence of a pressure at the metal/mould interface sufficient to overcome the anti-penetration surface forces, just as mercury requires a pressure to force it into a capillary ; this ' penetrating



(a) Metal (light), sand (grey), and voids (black). Unetched × 50

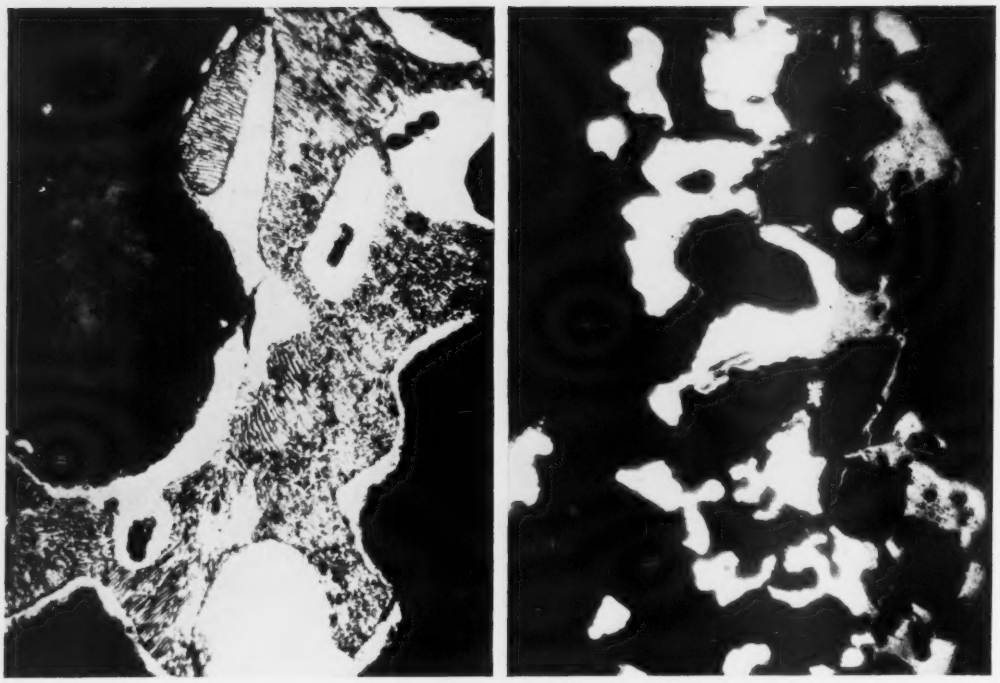
(b) Ferrite (light), pearlite, and sand (dark). Etched 2% nital × 150



(c) Enlargement of (b), showing resolved pearlite × 750

Fig. 5—Completely penetrated sand

Fig. 6—Moderately penetrated sand. Metal (light) slag (grey), and sand (dark). Unetched × 100



(a) Metal (light), slag (light grey), and sand (dark grey). Unetched × 50

(b) Ferrite (light), pearlite, and sand (dark). Etched 2% nital × 350

Fig. 7—Penetrated sand giving a clean peel

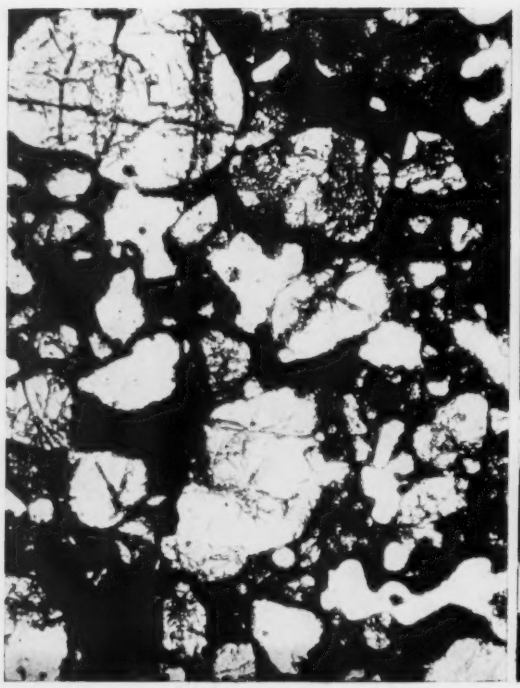


Fig. 8—Thin section of penetrated sand giving a clean peel. Viewed by transmitted light. Sand (light) metal (black) × 50

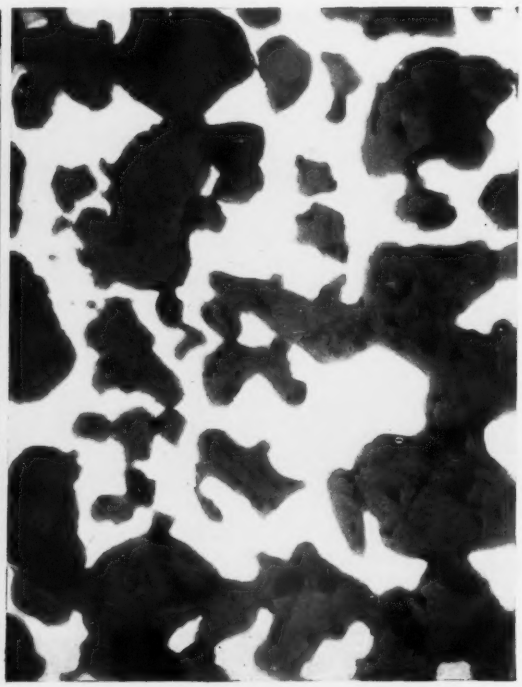
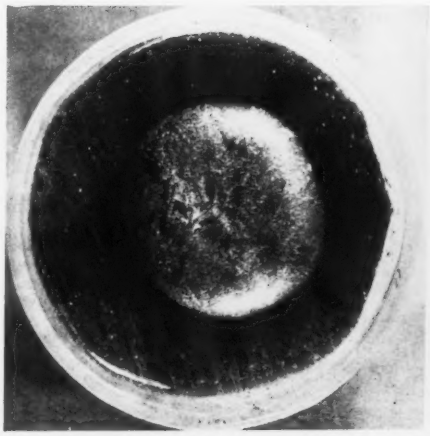
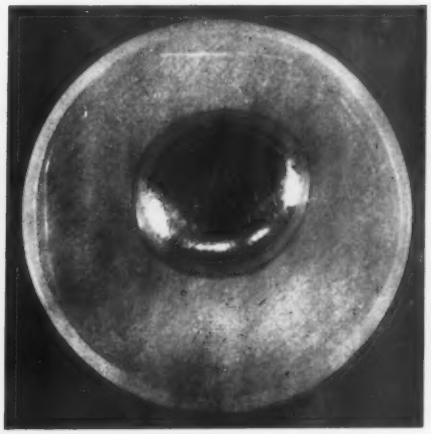


Fig. 9—Typical micro-photograph, showing metal (light), sand (grey), and voids (black) Unetched × 50

Fig. 10—Typical macro-photograph, showing penetration and silica sighting tube × 4

(a)

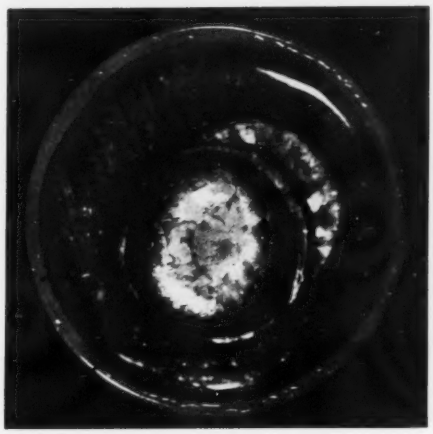




(b)

Fig. 11—Sessile drops. (a) Tin, (b) Armco iron, (c) Armco iron heated with free access of air (note spreading of oxide, but no spreading of metal) × 1·3

(c)



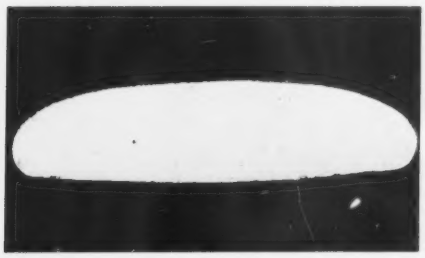
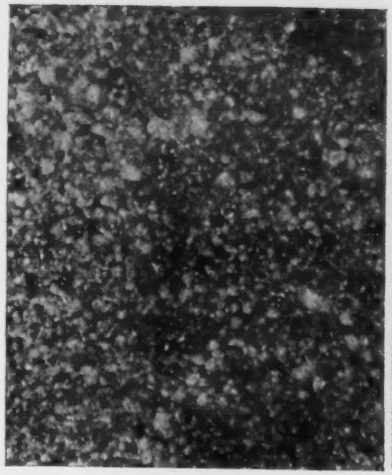
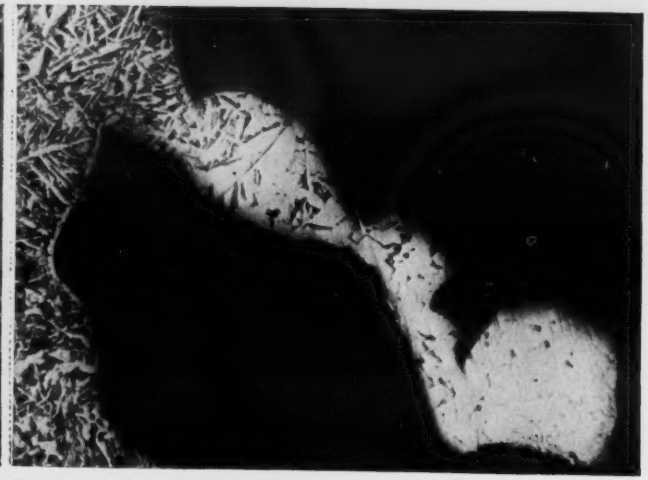


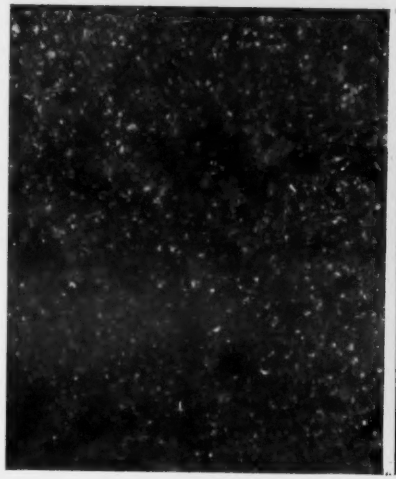
Fig. 12—Vertical cross-section of tin sessile drop. Oblique illumination × 3



(a)



(a) Furnace atmosphere slightly oxidizing, decarburization down the probe × 100

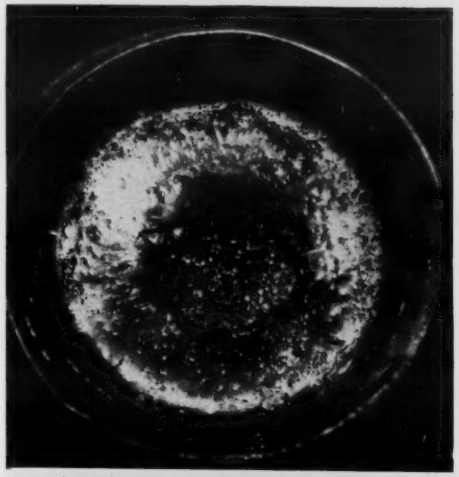


(b)

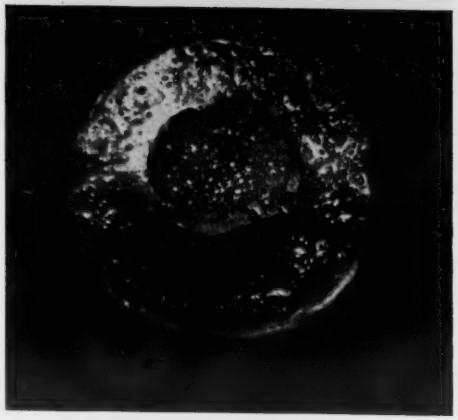
Fig. 13—Sand surface, heated in contact with molten tin to (a) 1550° C., (b) 1620° C. × 6

(b) Furnace atmosphere pure argon, no decarburization × 100

Fig. 14—Penetrating probes of steel H4183 into compacts of sand D. Etched 2% nital



(a)



(b)

Fig. 15—Armco iron, oxidized at a pressure of 16 cm. of oxygen, showing (a) glassy surface of clean peeling sand, (b) metal surface corresponding to sand of (a) × 1·5

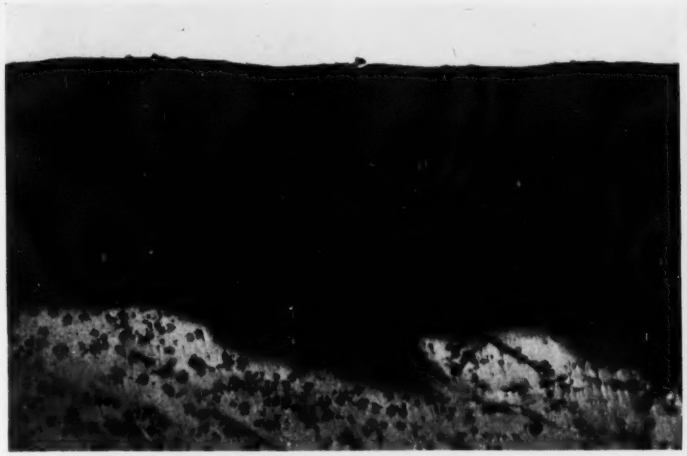


Fig. 16—Cross-section of metal and feebly adhering piece of slagged sand. Metal (light), slag (grey), and contraction gap (black) × 150

Fig. 17—Cross-section of clean peeling facing sand. Sand (dark grey), slag (light grey), and voids (black) × 75

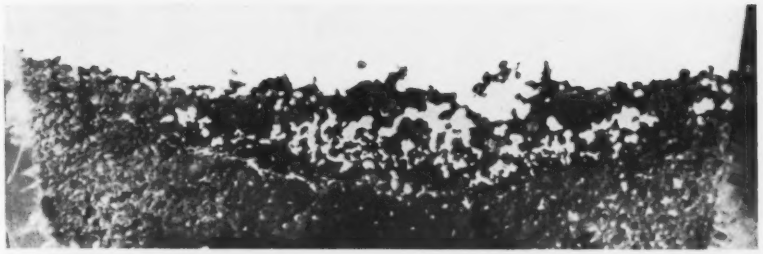


Fig. 18—Penetration through crack in silica wash × 4

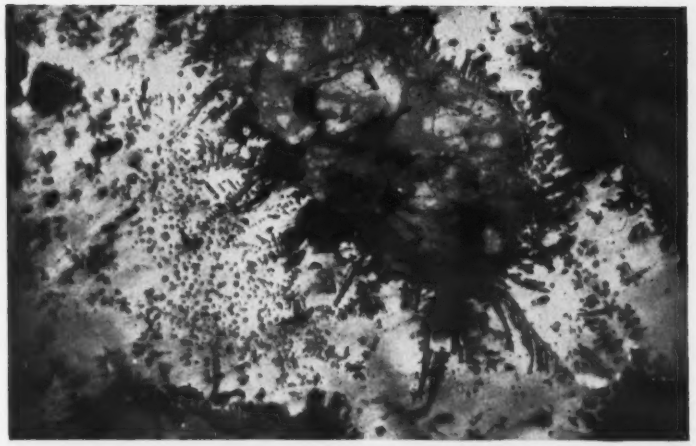


Fig. 19—Reaction between lime-silica wash A and sand grains. Sand (dark grey), slag (light grey), and voids (black). Note the darker constituent in the slag × 250

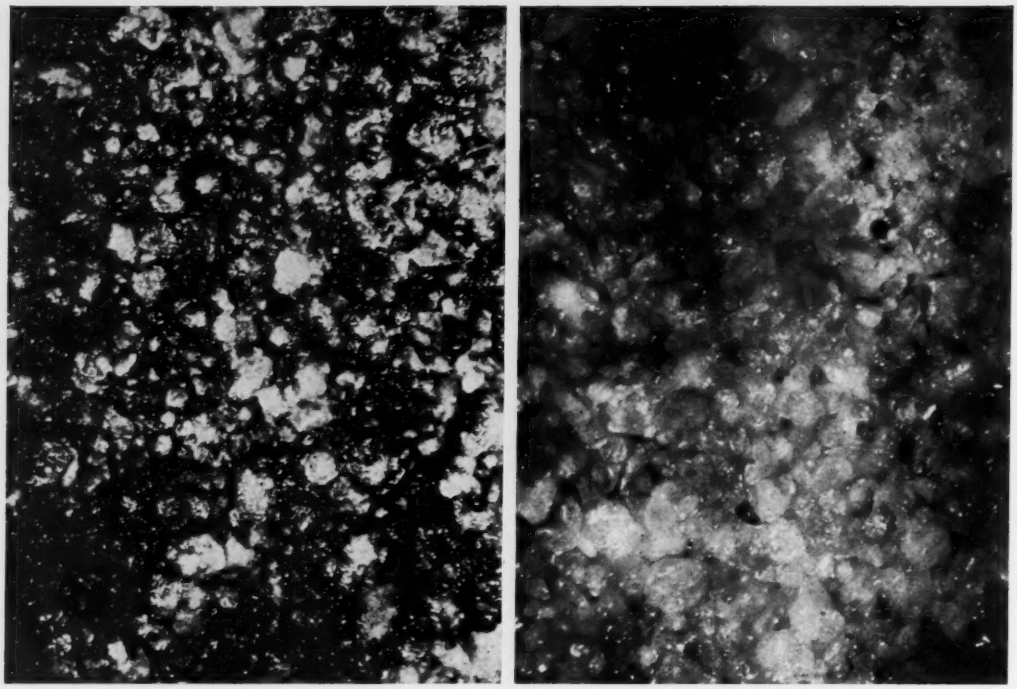


Fig. 20—Surface of sand D compact, held at 1600° C. for 0·5 min. after coating with a single wash of (a) FeO, (b) lime × 15

(a) Coated with lime–silica wash A. Sand grains protruding through the slag × 75

(b) Thickly coated with lime–silica wash A. Sand grains covered by slag. Clean peel × 75

Fig. 21—Facing layer of sand D compact. Sand (dark grey), slag (light grey), and voids (black)

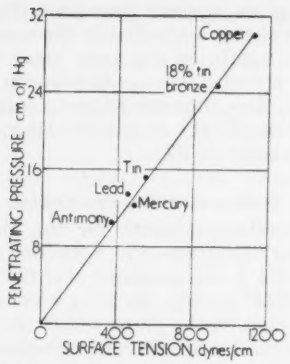


Fig. 22—Relation between penetrating pressure into F3 sand compacts and surface tension of molten metal[13, 14]

pressure ' is the metallostatic pressure of the molten metal at the interface.

Influence of Surface Tension of Molten Metal on Penetrating Pressure

Values of the penetrating pressure into F3 sand compacts were obtained for the following metals: mercury, lead, tin, antimony, copper, and an 18% tin bronze. The mercury experiment was carried out at room temperature, and the remainder at temperatures 50–300° C. above the melting points of the various metals. The temperatures below 600° C. were measured with a chromel–alumel thermocouple, and above 600° C. with the disappearing-filament pyrometer. The temperatures of the molten metals were controlled to within ± 10° C.

Figure 22 is a graph of penetrating pressure against the surface tension of the molten metal as obtained from the literature.[13, 14] The straight line through the origin indicates that the penetrating pressure is determined by the surface tension of the penetrating metal ; it indicates also that the contact angles of the various metals with silica are approximately the same, and that the radii of the interstices of the sand compacts are either constant or vary uniformly with temperature up to 1150° C., the temperature of the penetrating copper.

Figure 23 is a graph of the penetrating pressure, expressed as height of molten metal, against the ratio surface-tension/density for the metal. This graph shows that the height of metal necessary to give penetration is proportional to the surface tension divided by the density ; these properties of the metal are therefore fundamental in determining whether a casting of a given height will penetrate a given sand compact.

Relation between Air-Permeability Time of the Sand Compact and Penetrating Pressure

The permeability times for compacts made from sand mixes A–F, containing between 1 and 4% bentonite (Table III), rammed in the Gooch crucible, are shown in Fig. 24. The penetrating pressures of Armco iron at 1600° C. and tin at 750° C. were determined with these compacts, with the results shown in Fig. 25 ; the two close values of penetrating pressure for the 4% bentonite compact, obtained with two separate sand mixes, indicate the very fair degree of reproducibility obtained. The shape of the penetrating-pressure/bentonite-content curve is similar to that of the permeability-time/bentonite-content curve ; both show a maximum at approximately 2·0% bentonite. The shape of the permeability-time/bentonite-content curve is probably due to two opposing factors : with low bentonite contents, the controlling factor is the filling of the pores of the sand by the binder, with a resultant increase in permeability time ; but above 2·0% bentonite (Fig. 24), the increasing difficulty of compacting the sand (owing to the higher bentonite

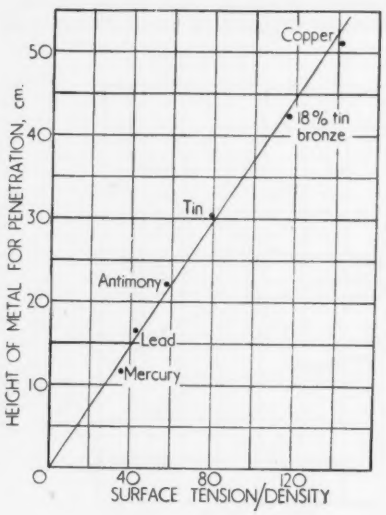


Fig. 23—Relation between penetrating pressure into F3 sand compacts and the ratio surface-tension/density for the molten metal

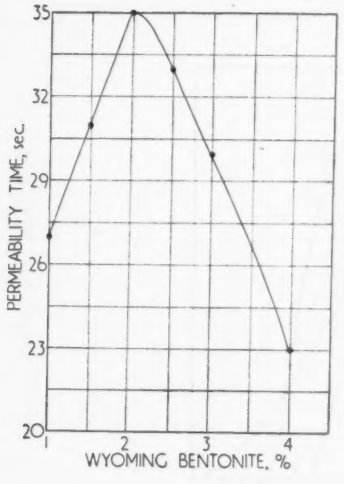


Fig. 24—Variation of permeability time with bentonite content of sand compacts

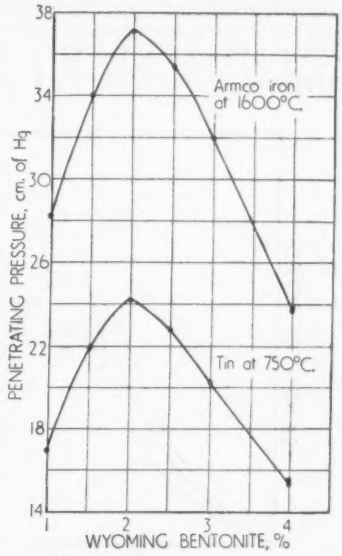


Fig. 25—Variation of penetrating pressures, for Armco iron at 1600° C., tin at 750° C., with bentonite content of sand compact

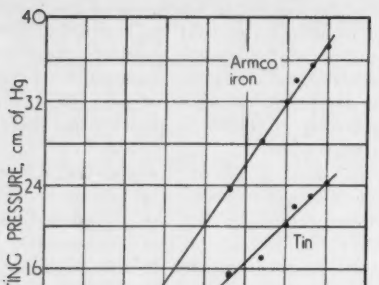


Fig. 26—Variation of penetrating pressure with permeability time, using sand compacts varying only in bentonite content

content) leads to an increase of pore radius and a consequent decrease in permeability time.

A rectilinear relationship is obtained when penetrating pressure is plotted against permeability time (Fig. 26), and the graph shows that for these sands the penetrating pressure is nearly proportional to permeability time ; extrapolation shows that zero penetrating pressure would be found with compacts still showing finite permeability times—a commonsense result.

When sand compacts of different grain-size distribution are compared, the penetrating pressure is not proportional to the permeability time. Thus, of compacts made from the three sands F1, F3, and F4/A (Table II), F1 has the lowest permeability time, yet its penetrating pressure values lie between those of F3 and F4/A (*see* Fig. 28). Perhaps this may be explained by considering the hypothetical curves for number of pores against pore area (Fig. 27) ; the permeability time is controlled by the number of pores and by the square of the pore area, whereas the penetrating pressure is controlled by the area of the largest pore ; thus although F1 has a smaller permeability time than F3 the areas of its largest pores may be less than those of F3.

Influence of Temperature on Penetrating Pressure

The penetrating pressure for tin, chosen for its relatively low vapour pressure, with compacts of sands F1, F3, and F4/A was measured over the temperature range 500–1650° C. ; Fig. 28 is a graph of the results. The dotted lines on the graph reflect the variation of the surface tension of tin with temperature ;[13] this is known to be rectilinear over the range 300–1050° C., and it is assumed that it remains rectilinear up to 1650° C. Each dotted line is calculated from the experimental point at 500° C., on the assumption that penetrating pressure is proportional to surface tension, that is, that the effective pore radius of the sand compact and the contact angle of tin with silica are constant with temperature. The results show, however, that the penetrating pressure falls more slowly than that so calculated up to 1350° C. ; this is probably caused by the swelling of the clay binders, leading to a decrease in effective pore radius of the sand with increase of temperature. Between temperatures of the order of 1400–1600° C. there is a marked decrease in penetrating pressure, for all three sands, to values well below those calculated as above. This is caused by sintering and fusion of the sand giving rise to a few larger pores ; photographs of sand surfaces that have been heated to 1550° C. and 1620° C. in contact with tin (Figs. 13*a* and *b*) illustrate the effect. Above 1650° C. there is a sudden increase in penetrating pressure for all three sands, owing to the formation of a glassy surface by nearly complete fusion of the sand.

The temperature at which the penetrating pressure suddenly decreases is probably between the *A* and

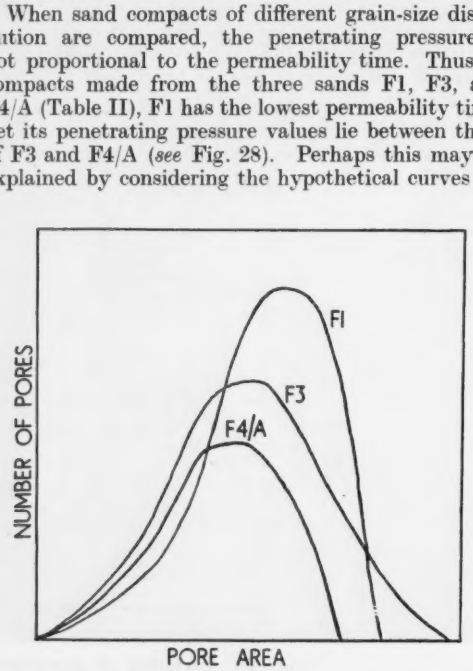


Fig. 27—Distribution curves for number of pores plotted against pore area (schematic)

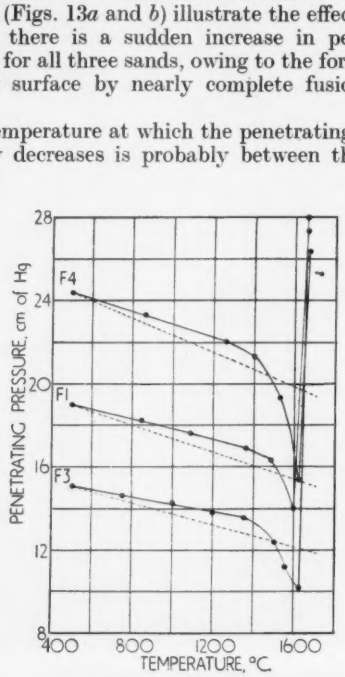


Fig. 28—Variation with temperature of penetrating pressure for tin

B sintering points* of the sand. The higher temperature at which the penetrating pressure suddenly increases no doubt corresponds approximately to the Seger cone value for the sand.

The influence of temperature on the penetrating pressure for Armco iron with two sands, F1 and F3, over a necessarily limited range, is shown in Fig. 29, in which it should be noted that the temperature scale is drawn much more openly than that of Fig. 28 ; rapid decrease in penetrating pressure with increasing temperature, caused by sintering and fusion of the sand, is again found.

Influence of Time at Temperature on Penetrating Pressure

In the standard experiment the metal is taken up to temperature in 2 min. and then held at temperature for 0·5 min. before pressure is applied. Experiments were carried out with Armco iron and sand mix D (2% bentonite) to investigate the variation of penetrating pressure with varying times at one temperature, *viz.*, 1600° C. The results are given in Fig. 30, the curve being similar in form to an isothermal sintering curve, where the sintering rate is most rapid initially. Increase of effective pore radius due to sintering, as already shown on page 8, is again apparent when the time at one temperature is increased ; the effects of increased time and temperature are, as expected, similar.

Influence of Carbon Content of Steel on Penetrating Pressure

Penetrating pressures for Armco iron and three steels, H4173, H4183, and En 9, with sand D, were determined over a range of temperature 1570–1630° C., approximately.

For the steels, the experimental technique was slightly modified : heating was carried out under a pressure of 10^{-3} cm. of Hg up to a few degrees below the melting point of the steel, when argon was admitted to the whole system until a pressure of about 70 cm. of Hg was attained ; differential pressure was then obtained on the upper side of the metal/sand

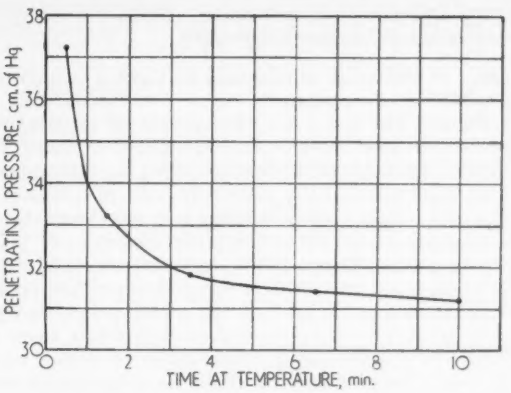


Fig. 30—Variation of penetrating pressure for Armco iron (with sand compact D) with time at temperature 1600° C.

interface by gradually evacuating the inner silica tube to which the Gooch crucible was fused. This technique had to be used to prevent the excessive gas evolution that occurs in steels at low pressures ; similar experiments were carried out with Armco iron, and there was no discrepancy between the results and those obtained by the normal technique.

The results are shown in Fig. 31. The drop in penetrating pressure, for all the steels as compared with the Armco iron, is somewhat larger than would be expected from a change in surface tension of the metal, and may be partly caused by a change in contact angle ; reaction between the carbon of the steel and the silica of the sand is thermodynamically possible at the temperatures and low oxygen partial pressures concerned, and this reaction, even if confined to the surface layers of the metal, might well decrease the contact angle. It is perhaps significant that the penetrating pressure for these four ferrous materials, at any one temperature, decreases in the same order as the carbon content increases (Table I), the relation

* The *A* sintering point is the lowest temperature at which the platinum ribbon in the platinum-ribbon sintering point apparatus makes a **V** when lifted off the sand specimen.[15] The *B* sintering point is the lowest temperature at which smaller grains can be seen at a low magnification (× 20–25) to start to fuse.[16]

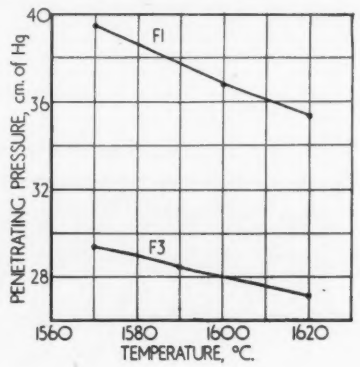


Fig. 29—Variation with temperature of penetrating pressure for Armco iron

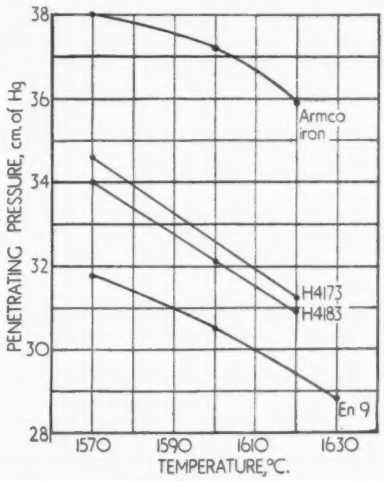


Fig. 31—Variation of penetrating pressures for Armco iron and steels H4183, H4173, En 9 (with compacts of sand D) with temperature

being approximately rectilinear. Further work with more steels is evidently necessary.

Effect of Oxidizing Atmosphere on Carbon Content of Steel

Figures 14*a* and *b* are photographs of penetrating probes of steel H4183 into compacts of sand D. Figure 14*a* is the result obtained when the atmosphere was slightly oxidizing (moisture was not removed from the argon) ; decarburization down the probe is most marked, the tip of the probe consisting of pure ferrite grains. Figure 14*b* is the result obtained with purified argon ; the carbon composition of the probe appears similar to that of the metal pellet, except that at the microscopic metal/silica interface there is evidence of a thin layer substantially of ferrite, such as would be produced by slight decarburization due to silica (as discussed previously).

Influence of Oxidation on the Penetrating Pressure for Armco Iron with Compacts of Sand D

A series of experiments was carried out to investigate the influence of oxidation of the penetrating metal on the penetrating pressure, using Armco iron at 1600° C. and compacts of sand D. The apparatus was evacuated to a pressure of 10^{-3} cm. of Hg as before, after which oxygen was admitted to the system until the desired oxygen pressure was attained. The specimen was then heated to 1600° C. in 2 min. ; during the course of the heating the oxygen pressure rapidly decreased, owing to oxidation of the metal. The specimen was held at temperature for 0·5 min. and then pressure was applied to the metal surface.

The results are shown in Fig. 32 ; the reproducibility is poor, but it is clear that the penetrating pressure increases with increasing oxygen pressure, *i.e.*, with increasing oxidation of the metal surface. We consider that this effect is consequent upon reaction of the surface sand with the iron oxide on the metal surface to form viscous iron silicates which partially block the surface pores, so that higher pressures are needed to give penetration. The viscous silicates solidify on penetrating to the cooler layers of the sand, and if complete blockage results (Fig. 33), no metal penetration can occur. This is shown by the specimen oxidized at an oxygen pressure of 16 cm. ; no penetration occurred and the metal was found to be in contact with a glassy layer of slag. Figures 15*a* and *b* show the sand surface and metal surface respectively ; there was a small piece of slagged sand adhering, though only feebly, to the metal, and micro-examination showed that this sand was not penetrated by metal (Fig. 16). Figure 17 is a micrograph of a cross-section of the facing sand that peeled cleanly from the metal ; the blockage of the pores by glassy iron silicate is evident. An X-ray photograph of the slagged sand surface (crushed to 300 mesh, silica partially removed by gravity separation in bromoform) was taken, using $FeK\alpha_1$ and $FeK\alpha_2$ radiation ; this confirmed the suspected presence of fayalite.

Influence of Silica, Oxide, and Slag Washes on the Penetrating Pressure

This section records the influence of various mould washes, including metal oxide and slag washes, on the penetrating pressure. Washes based on iron oxides and silicates, and also on lime, were tested with a view to the production of slag barriers that might block the pores and prevent metal penetration in the same way as the viscous silicates discussed above. The compositions of the washes used are listed in Table IV (*see* page 4) ; the results, summarized in Table V, have the salient features given below.

Silica washes (Runs 1–3) give rise to penetrating pressures almost identical with those for untreated sand compacts ; this indicates wash cracking, which is confirmed by a vertical cross-section of one of the relevant specimens (Fig. 18). If the depth of sand heated to above the melting point of the molten metal is small, a silica wash will localize penetration to the few points where cracking has occurred ; moreover, the wash, with a lower heat conductivity than the coarser facing sand, will tend to minimize the depth of sand heated to above the metal melting point. However, when there is a deep layer of sand at temperatures above the metal melting point, as may occur in heavy castings and especially at re-entrant angles or cores, metal will penetrate cracks and then mushroom out into the hot sand layer, as shown in Fig. 18. This explains how the surface layers of silica-washed moulds can be prised away from the surface

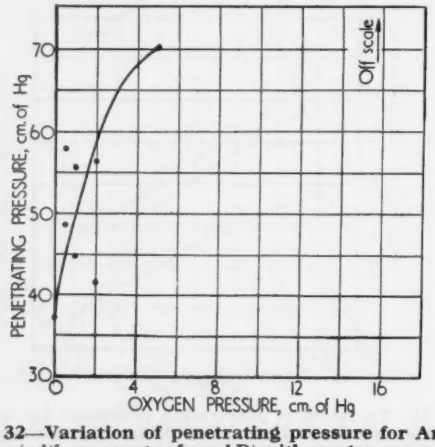


Fig. 32—Variation of penetrating pressure for Armco iron (with compacts of sand D) with oxygen pressure

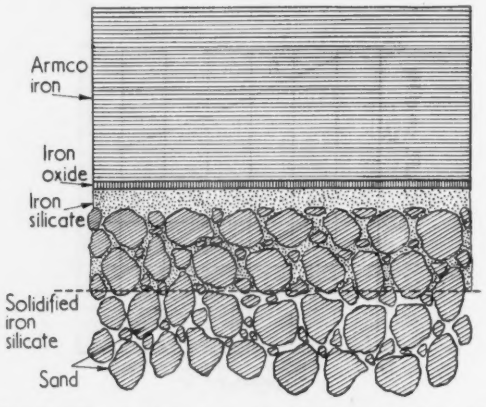


Fig. 33—Prevention of penetration by formation of iron silicate (schematic)

Table V—INFLUENCE OF WASHES

Metal : Armco Iron ; Sand : D (Table III) ; Temperature : 1600° C. ; Heating Cycle : 20° C. to 1600° C. in 2 min., and 0·5 min. at 1600° C., before pressure application. Penetrating pressure of unwashed sand at 1600° C. : 37·2 cm. of Hg. All washes applied by painting

No.	Wash	Details of Application	Penetrating Pressure, cm. of Hg	Remarks
1	Lloyd's silica wash	Single coat on the green sand surface	37·0	Wash cracking—confirmed by macro-section (Fig. 18)
2	Lloyd's silica wash	Single coat on the green sand surface. Flame dried, resulting cracks filled in with further wash	39·6	Wash cracking—penetrated layer of adhering sand could be prised off
3	Lloyd's silica wash	Two coats, the first flame dried before application of the second	39·0	" " " "
4	FeO composition wash	Single coat on the green sand surface	19·8	Uniform penetration. Increase of effective pore radius due to slagging
5	FeO composition wash	Single coat on the green sand surface	20·8	" " " "
6	Fe_3O_4 wash	Single coat on the green sand surface	29·2	" " " "
7	Fayalite composition wash A	Single coat on the green sand surface. Flame dried, cracks filled in	22·6	" " " "
8	Fayalite composition wash A	Two coats, the first flame dried before application of the second	40·2	Uniform penetration
9	Fayalite composition wash B	Two coats, the first flame dried before application of the second	51·2	Penetration at a few points ; some blockage of larger pores by wash
10	Fayalite composition wash C	Single coat on the green sand surface. Very difficult to apply	30·4	As for 4
11	Fayalite wash	Single coat on the green sand surface	25·6	" "
12	Silica-rich iron-silicate wash	Single coat on the green sand surface. Flame dried	22·5	" "
13	Silica-rich iron-silicate wash	Two coats, the first flame dried before application of the second	38·0	Uniform penetration
14	Silica-rich iron-silicate wash	Three coats, each flame dried before application of the next	No metal penetration	Metal peeled cleanly from slagged sand surface
15	Double wash of silica and fayalite composition wash B	Silica wash on the green sand surface, then fayalite composition wash B	37·0	Wash cracking
16	Double wash of silica and fayalite composition wash B	Two washes of silica, and then two washes of fayalite composition wash B ; each wash flame dried before application of the next	50·2	As for 9
17	Lime wash	Single coat on the green sand surface	32·0	As for 4
18	Lime wash	Three coats, each flame dried before application of the next. Wash dried at about 800° C.	47·4	Penetration by slag at zero pressure—few grains of adhering and penetrated sand
19	Lime–silica wash A	Three coats, each flame dried before application of the next. Wash dried at about 800° C.	No metal penetration	Penetration by slag at zero pressure—the metal peeled from the slagged sand surface (Fig. 21*a*) but a few grains adhered to its surface
20	Lime–silica wash A	As for 19, but slightly thicker coats	No metal penetration	Penetration by slag at zero pressure—the metal peeled cleanly from slagged sand surface (Fig. 21*b*)
21	Lime–silica wash B	Two coats, the first flame dried before application of the second. Wash dried at about 800° C	No metal penetration	The metal peeled cleanly but had a furrowed surface ; furrowing probably due to very viscous wash
22	Lime–silica wash C	Two coats, the first flame dried before application of the second. Wash dried at about 800° C.	40·0	Wash cracking
23	Alumina–silica wash	Two coats, the first flame dried before application of the second	39·0	Wash cracking

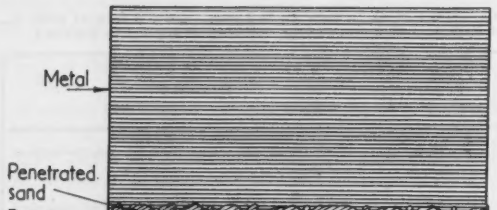


Fig. 34—Result of application of incomplete slag wash (schematic)

of castings even when considerable penetration has occurred.

Thin washes containing iron oxide (Runs 4–6) all lead to a decrease in penetrating pressure as compared with that for untreated compacts. This is probably because when the iron oxide melts to a relatively non-viscous liquid (about 0·2 poise at 1400° C.), it readily flows through the sand, and the resultant slagging occurring in the pores increases the effective pore radius, as indicated schematically in Fig. 34. Partial reaction of the facing sand with the iron oxide is evident in Fig. 20*a*, which is a photograph of a sand compact surface coated with an iron oxide wash and held at 1600° C. for 0·5 min. If there were a sufficient supply of iron oxide at the compact surface, the metal could be in contact with a continuous thick layer of molten iron silicates, and penetration would be prevented. Unfortunately the thick iron oxide washes melted and rose around the metal before sufficient reaction with the sand, and the resultant formation of viscous silicates, could occur.

The iron silicate washes (Runs 7–14), being more viscous when molten than the iron oxide, remained in position. The reproducibility of results with fayalite composition washes, and silica-rich iron-silicate washes, was poor, but the results indicate that the penetrating pressure increased with heavier coats of wash. Composite washes of silica and slag (Runs 15 and 16) led to similar results.

Results obtained with lime and lime–silica washes were again similar. Figure 20*b* is a photograph of a sand compact surface coated with a single lime wash and held at 1600° C. for 0·5 min. ; there is evidence of slagging leading to several large pores. The results for lime washes (Runs 17–18) show that the penetrating pressure increases with heavier coats of wash. In the three-coat lime–silica wash (Run 19), penetration of the sand by a relatively poorly conducting slag was recorded on the ohmmeter before any pressure had been applied to the metal. Nevertheless this wash prevented metal penetration, and the metal peeled fairly cleanly from the slagged sand surface, although there were several grains of sand adhering. In this experiment the amount of wash applied was just insufficient to fill the pores in the sand, from a depth at which the temperature of the sand was equal to the solidification point of the slag to the upper surface of the sand grains in contact with the molten metal. Figure 21*a*, a typical cross-section, shows the facing layer of sand that peeled cleanly from the few grains adhering to the metal. When a still thicker lime–silica wash of the same composition (Run 20) was applied, a clean peel with no adhering sand was obtained ; Fig. 21*b* shows a typical cross-section of the cleanly peeling surface, which is a continuous slag layer. Figure 19 shows the reaction between the lime–silica wash and the sand grains. Experiments were carried out with other lime–silica washes, of differing lime content and consequently of differing viscosity and melting and solidification points, and also with a high melting-point alumina–silica wash (Runs 21–23). These high-melting-point washes crack in a similar manner to silica washes, and contrast markedly with the relatively fluid and low-melting-point washes.

These preliminary experiments on mould washes show that metal penetration may, in some cases, be prevented by washes that form slag with the sand. They suggest that, from the practical point of view, the ideal wash should melt just below the pouring temperature of the metal to a fairly viscous slag, so as to produce from a minimal thickness of wash a continuous layer at the metal/mould interface. Further systematic work on washes is desirable and we hope to initiate it shortly.

Alumina-Sand Mixes

A few experiments were carried out with alumina-sand mixes of the same composition as the silica-sand mix D. The reproducibility of the penetrating pressure was very poor, values of 21·9, 13·8, and 11·4 cm. of Hg being obtained for a triplicate experiment, although the permeability times for the green compacts showed good reproducibility similar to that obtained in the silica-sand experiments. This lack of reproducibility is probably because of the disruption of the compacts during heating owing to the relatively large thermal expansion of alumina. The good reproducibility of the penetrating pressure values for silica-sand mixes, and the smoothness of the curves in Fig. 28, indicate that silica-sand compacts withstand thermal expansion well, and have little tendency to crack or disintegrate ; doubtless the low thermal expansion of silica is responsible for this good behaviour.

DEPTH OF METAL PENETRATION

It may be assumed that molten metal will flow into the compacted sand until the tip of the advancing probe solidifies, *i.e.*, to a depth where the temperature is equal to (or is a little less than) the solidification point of the metal, and therefore that the depth of penetration will be controlled by the thermal diffusivity of the sand. If it is also assumed that the temperature T_s of the metal/mould interface remains constant, then, by considering the sand mould as a body extending to infinity in one direction, it may be shown that, after a time t sec.,

$$\frac{T - T_s}{T_o - T_s} = \frac{2}{\sqrt{\pi}} \int_0^{\frac{x}{2\sqrt{at}}} e^{-\beta^2} . d\beta \quad \ldots\ldots\ldots\ldots \quad (1)$$

where :

T_o = initial temperature of sand, ° C.
α = thermal diffusivity of sand
x = distance from metal/mould interface, cm.
T = temperature, ° C., at distance x cm.

This equation can be used to obtain a semi-quantitative picture of how various physical conditions of the sand and metal influence the depth of penetration.

The time t that the metal in contact with the sand remains molten depends on the pouring temperature of the metal, the size of the casting, and the thermal diffusivity and geometry of the sand mould.[17, 18]

The temperature T_s of the metal/mould interface will naturally be less than the pouring temperature of the molten metal, owing to the chilling action of the mould. In the present treatment of the problem, T_s is assumed to remain constant ; we think this involves no serious error.

The thermal diffusivity α of the sand is equal to the thermal conductivity divided by the product of the density and specific heat. Very little is known about the thermal diffusivity of sand agglomerates at temperatures of the order of 1600° C. ; however, measurements have been made of the thermal conductivity of various agglomerates up to about 1250° C.[19, 20] The observed thermal conductivity increases markedly at high temperatures, because it is made up of true conductivity and a term due to radiation, the increase being greater the larger the grain size of the sand (Fig. 35). Approximate theoretical treatments[21, 22] lead to the equation

$$k = k_o + ArT^3,$$

where :

k = observed conductivity
k_o = true conductivity
A = constant
r = mean radius of sand grains
T = absolute temperature.

The equation is in good agreement with the experimental results, and if these are extrapolated by means of it to 1600° C. (Figs. 35 and 36), a measure of the conductivity at high temperatures is obtained. This naturally ignores effects such as sintering, which will

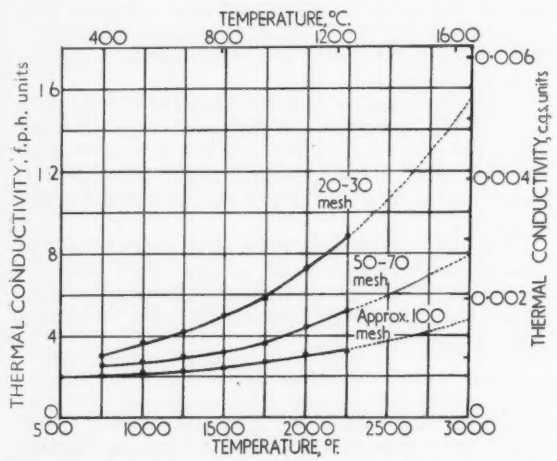


Fig. 35—Variation of thermal conductivity of three sands with temperature (after Lucks, Linebrink, and Johnson[19])

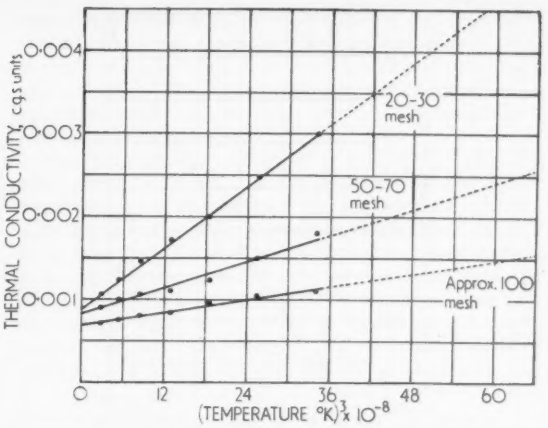


Fig. 36—Extrapolation of the thermal conductivity data (Fig. 35) by means of the equation $k = k_o + ArT^3$

probably increase the thermal conductivity because it increases the density of the sand compact ; the thermal conductivity of sand compacts increases with increasing density, because silica has a thermal conductivity higher than that of the gas in the pores.

Using these approximate values for the various terms, equation (1) may be solved by using tables of the probability integral or error function

$$\Phi\left(\frac{x}{2\sqrt{\alpha t}}\right) = \frac{2}{\sqrt{\pi}}\int_0^{\frac{x}{2\sqrt{\alpha t}}} e^{-\beta^2}.d\beta$$

It is possible to employ the equation to show various relationships :

(1) The dependence of the depth of penetration on the thermal conductivity of the sand, *i.e.*, on the grain size of the sand (Fig. 37) ; the depth of penetration increases with increase of grain size, in agreement with experiment.[5, 6] Since the air permeability increases and the sintering point rises with increase of grain size, the often observed correlation between depth of penetration and these properties is also readily explained.

(2) The dependence of the depth of penetration on amount of superheat (Fig. 38) ; here the increased sintering of the sand at the higher temperatures, with

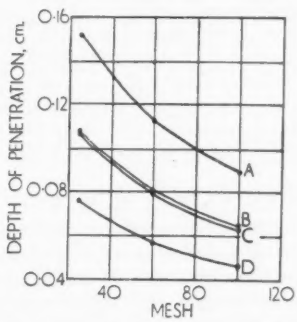


Fig. 37—Variation of depth of penetration with sand mesh (theoretical). T = 1480° C., T_o = 20° C. Curve A: T_s = 1650° C., t = 60 sec.; curve B: T_s = 1600° C., t = 60 sec.; curve C: T_s = 1650° C., t = 30 sec.; curve D: T_s = 1600° C., t = 30 sec.

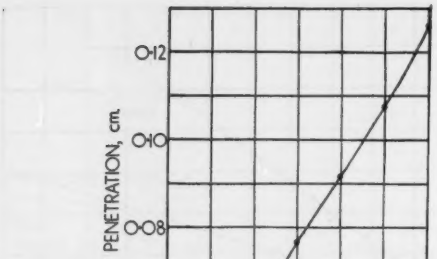


Fig. 38—Variation of depth of penetration with temperature of metal/mould interface (theoretical). Sand, 20–30 mesh ; $T = 1480°$ C. ; $T_o = 20°$ C. ; $t = 30$ sec.

Fig. 39—Variation of depth of penetration with the time that the metal at the metal/mould interface remains molten. Sand, 20–30 mesh; $T = 1480°$ C.; $T_o = 20°$ C.; $T_s = 1600°$ C.

its consequent effect on the thermal conductivity, and also the increased time for which the metal remains molten, have to be ignored. With increased superheat the depth of penetration increases, a qualitatively obvious effect frequently observed in practice.

(3) The dependence of the depth of penetration on the time the metal at the metal/mould interface remains molten (Fig. 39). As expected, the depth of penetration increases with this time.

The theory is only semi-quantitative, but it is interesting to see that the values obtained for the depth of penetration (Figs. 37, 38, and 39) are of the same order as values observed in practice.

It should be noted that the depths calculated are conservative, because only the initial penetration in the sand compact, to a depth that is already heated to the metal solidification point when penetration begins, has been considered. The sand will generally continue to heat up in depth after this initial penetration, especially since the now penetrated layers will have much higher thermal conductivity; thus remelting of the penetrating probes, with a further slow penetration, is to be expected. The effect will naturally be greatest in re-entrants and cores, where the rate of heat extraction by and through the sand is least, and it is, of course, in such parts of sand moulds that the greatest depth of penetration is found in practice. The effect will also be important in runners, where the rate of heat arrival from the pouring metal is greatest, and may in part explain the prevalence of penetration found there.

RATE OF PENETRATION OF METAL AND SLAGS

It has sometimes been thought that the process of metal and/or slag penetration into sand moulds is low because of the viscous forces opposing penetration. It is shown below that the viscosity of the molten metal or slag is not a limiting factor in controlling the rate of penetration.

If we consider the sand compact to have n pores of average radius r cm., then from Poiseuille's equation we have :

$$\frac{dv}{dt} = \frac{np\pi r^4}{8l\eta}$$

where :

v = volume of liquid entering pores, c.c.
l = mean length to which liquid enters, cm.
t = time taken, sec.
p = mean pressure difference, dynes/sq. cm., between the mouth of the pores and the tips of the advancing metal probes
η = viscosity of penetrating liquid, poise.

Now, $$dv = n\pi r^2 dl,$$

whence $$dt = \frac{8\eta}{pr^2}\, l.dl$$

and $$t = \frac{8\eta}{pr^2}\int_o^l l.dl = \frac{4\eta l^2}{pr^2} \qquad \ldots\ldots\ldots\ldots\ldots (2)$$

From this equation, the time taken for molten metals or slags to penetrate into sand compacts may be calculated. It is convenient to consider penetration in a horizontal direction so as to avoid the complication of gravitational force.

For molten metals, p is the excess of the metallostatic pressure over the critical penetrating pressure. Thus for $p = 1$ cm. of Hg, and $r = 5 \times 10^{-3}$ cm.,* we may calculate that tin or iron ($\eta \simeq 0{\cdot}02$ poise[23, 24]) penetrates to a depth of 0·5 cm. in approximately 0·06 sec.

For slags, which wet silica, p is the sum of the metallostatic pressure and a term $2\sigma/r$, where σ dynes/cm. is the surface tension of the slag, so that, when the metallostatic pressure is zero, we obtain by substitution in (2):

$$t = \frac{2\eta l^2}{\sigma r}.$$

Thus a slag with $\eta \simeq 1$ poise and $\sigma \simeq 500$ dynes/cm.[25] penetrates to a depth of 0·5 cm. in approxi-

* Typical magnitude calculated from penetrating pressure experiments.

mately 0·2 sec., even when the metallostatic pressure is zero.

These calculations show that the initial penetration of molten metal or slag into a sand compact is very rapid, the liquid penetrating in a fraction of a second to the depth of sand heated above the appropriate solidification point. Penetration is checked by the solidification of the advancing probes of liquid as they reach sufficiently cool depths in the compact, and not by an initially high liquid viscosity. Further penetration can occur afterwards, much more slowly, if the compact heats through and the probes of metal or slag re-melt ; the rate and extent of such secondary penetration is also limited by the rate of heat flow in the compact, not by viscosity considerations.

INFLUENCE OF RATE OF POURING ON THE PRESSURE AT THE METAL/MOULD INTERFACE

The influence of the kinetic energy of the pouring metal on the metallostatic pressure at the metal/mould interface has so far been neglected, but it may easily be shown to be unimportant.

Consider a mould of height H cm., containing h cm. of molten metal of density ρ g./c.c., into which molten metal is being poured at the rate of R cm./sec. The velocity, v cm./sec., of the molten metal, after falling through a height $(H - h)$ cm., is given by :

$$v = \sqrt{2g(H - h)}$$

Therefore :

Kinetic energy pressure on base of mould
= momentum destroyed/sec./sq. cm.
= $R\rho\sqrt{2g(H - h)}$ dynes/sq. cm.

By substituting typical values in this expression it may be shown that, unless the rate of pouring is very fast or the layer of poured metal very shallow, the pressure due to the kinetic energy of the molten metal is very small compared with that due to its static thrust, $g\rho h$ dynes/sq. cm.

DISCUSSION

We can now use the above experimental results and theoretical considerations to obtain a picture of what happens at the metal/mould interface during steel casting, and to see how the incidence and extent of metal penetration are influenced by the various factors involved.

As the metal is poured, it comes into contact with cold sand ; a very thin metal layer in contact with the sand may solidify momentarily, but it quickly re-melts because the rate of heat extraction by the warming sand soon becomes less than the rate of heat supply from the metal bulk. Since molten metal does not wet silica, no penetration occurs until the metallostatic pressure (together with any very small extra pressure due to the kinetic energy of the falling metal) reaches a critical value, the penetrating pressure investigated above, but the sand mould continues to heat up in depth as it extracts heat from the metal. If and when, for the particular conditions existing, the penetrating pressure is reached—it will be of the order of 50 cm. of metal, for steel in average moulds—metal penetrates in a fraction of a second to the depth of sand heated to the solidification point of the metal, and there solidifies. If the sand continues to heat through (as it will while the degree of metal superheat remains large enough) and especially if the rate of heat extraction by and through the sand is small enough, the penetrating metal probes re-melt and a further slow penetration occurs, dependent in rate and extent on the heat flow in the mould, and not on metal viscosity.

The penetrating pressure, p dynes/sq. cm., the attainment of which is a necessary condition for penetration, is determined by the surface tension, σ dynes/cm., of the molten metal, the contact angle θ it makes with silica, and the effective pore radius, r cm., of the compacted sand, in accordance with the usual formula $p = -(2\sigma\cos\theta)/r$. For ferrous materials at casting temperatures, it is probable that the surface tension and contact angle are substantially constant (this is further discussed below) ; the penetrating pressure is thus determined by, and is approximately inversely proportional to, the effective pore radius.

The effective pore radius as herein defined is a quantity related to the dimensions of the larger pores, since it is into only these that metal flows when the penetrating pressure as measured by the present technique is reached. It is initially determined by the sizes of the sand grains, the composition of the sand mix, and the other physical characteristics of the sand as compacted ; it may also be markedly modified by sintering and fusion at the high temperature involved in steel casting, and by slagging of the sand particles with oxides present at the metal/mould interface.

The effective pore radius increases with general increase of sand grain size, and is also markedly influenced by the size distribution ; the common practice of mixing coarse and fine sand to obtain good packing probably leads to an effective pore radius near to that which the finer sand would give if compacted alone. We have shown that both the air permeability and the penetrating pressure for sand compacts having constant sand composition vary considerably, and in a like manner, with the proportion of bentonite added as binder, but that the variations of air permeability and of penetrating pressure between compacts of different sand compositions are not parallel. This is because the total porosity for air permeation, when the size distribution of the pores is not constant, bears no simple relation to the effective pore radius for metal penetration, since air permeation is limited by viscous flow of air in all the pores, whereas metal penetration is limited by surface forces at the larger pores.

The extensive modification of the effective pore radius of sand compacts by heating is evidently of great importance in practical casting. The present experiments have shown that there is a small decrease in effective pore radius as the compact is heated to about 1200° C., probably caused by expansion of binder ; this has a favourable influence in hindering penetration, which partly offsets the unfavourable influence of the decrease of metal surface tension with increasing temperature. However, between about 1300° C. and 1650° C.—which includes the usual range of steel casting temperatures—incipient sintering of the compact leads to a considerable increase in effective pore radius because a few large pores are formed ;

the great decrease of effective pore radius found above 1650° C., owing to the closing up of pores by further sintering and softening, occurs at temperatures outside the useful casting range. Such heat modification of the mould as occurs during steel casting is therefore unfavourable, tending to make metal penetration less difficult.

Silica washes, long used in practice, have been shown in the present investigation to have little influence on penetrating pressure, because they crack and thus scarcely alter the effective pore radius. However, their use reduces the number of penetrating metal probes per unit area of metal/mould interface, so that sand adherence, even though there may be considerable penetration beneath the wash because of metal spreading sideways from the probes, is lessened when such washes are used.

Metal oxidation at the metal/mould interface can lead to the production of iron silicates viscous enough to remain there and not float up through the metal. These slaggy materials wet silica and thus penetrate pores without any applied pressure ; we have shown that the extent of this penetration is limited by solidification rather than by viscosity, and hence by the thermal diffusivity of the sand compact. Slag penetration can greatly reduce the effective pore radius, probably in favourable cases to zero, and it is clearly a very important practical factor preventing metal penetration and leading to clean-peeling sand.

If iron oxides are deliberately applied to the surface of the sand compact as a wash, molten oxide can react with silica *within* the pores and actually increase the effective pore radius. Washes made from mixtures or compounds of iron oxides or lime with silica can, however, be very effective in sealing the sand pores and entirely preventing metal penetration. Further systematic work on such washes, aiming at the production of a continuous, non-porous mould surface such as sand itself would give at about 1700° C., but at the lower temperatures obtaining in steel casting, might have considerable interest. It should be emphasized that their action is quite different from that of the commonly used silica washes which, as explained above, limit metal penetration to a few points where cracks occur, and remain relatively unfused.

The present penetrating pressure results, for a few steels differing mainly in carbon content, indicate a lowering of penetrating pressure with increase of carbon content (Fig. 31) ; this may well be caused by a reduction of surface tension. The assumption of substantially the same contact angles with silica for all the non-ferrous metals used is justified (for the metals under nearly oxygen-free conditions) by the near-proportionality of penetrating pressure and surface tension (Fig. 22) ; for iron, there is no evidence of any great change of contact angle even when a substantial amount of oxidation of the metal has occurred. While there is nothing inconsistent with physical theory in these assumptions, further fundamental work on metal surface tensions and contact angles with silica and oxides at high temperatures is clearly desirable, and we hope to begin it in the near future.

The present experiments have only incidental bearing on the rate and extent of metal penetration, although the reproducibility of the penetrating pressure values, coupled with micro-examination of penetrated sand compacts, has indicated that penetration, once it occurs, does so within a fraction of a second and to a depth of the order of a few millimetres. The theoretical calculations on pages 12–15, although obviously approximate, confirm these magnitudes, and the depth of penetration found is also in agreement with practical experience. Thus the attainment of the penetrating pressure is usually both the necessary and sufficient condition that undesirable penetration should occur. Of course, if other considerations make it possible to pour a casting with a small degree of superheat, so that rapid final solidification of the metal at the metal/mould interface occurs before the penetrating pressure is reached, there will be no penetration. From the point of view of preventing penetration, therefore, a large casting ought to be poured with as small a degree of superheat, and as slowly, as possible.

SUMMARIZED CONCLUSIONS

(1) Molten metals do not wet silica.

(2) Molten metals penetrate into sand compacts only when the metallostatic pressure at the metal/sand-compact interface exceeds a critical value, the 'penetrating pressure.' For iron and steel with average sand compacts, it is of the order of 20–60 cm. of Hg, or 35–110 cm. of iron or steel.

(3) For a given sand compact, the penetrating pressures for copper, tin bronze, tin, lead, mercury, and antimony are proportional to the surface tensions of the metals.

(4) The penetrating pressure for iron increases with decrease of sand grain size, since this gives a decrease of effective pore radius.

(5) The penetrating pressure for iron and steel is decreased by sand sintering at normal steel casting temperatures, but increased by the considerable fusion induced at higher temperatures.

(6) The penetrating pressure for iron at 1600° C. (and for tin at 750° C.) is nearly proportional to the air-permeability time at 20° C., for sand compacts having the same grain-size distribution and differing only in binder (bentonite) content ; each shows a maximum at about 2% bentonite.

(7) The penetrating pressure for iron increases with increasing surface oxidation of metal, owing to the formation of ferrous silicates that partially plug the pores in the sand compact.

(8) The penetrating pressures for three steels under non-oxidizing conditions are somewhat lower than those for iron under similar conditions, and decrease with increase of carbon content.

(9) Silica mould washes crack and have little influence on penetrating pressure, but localize penetration and tend to reduce sand adherence.

(10) Washes made of mixtures or compounds of lime or iron oxide with silica melt to a viscous slag that wets silica and enters pores without application of pressure ; if thick enough, the slag completely seals the pores and covers the sand grains with a continuous

viscous layer that prevents metal penetration and sand adherence.

(11) Sand compacts are penetrated in a fraction of a second by molten metals and slags, to depths determined by the thermal diffusivity of the compact and the degree of superheat of the fluids and not by their viscosities.

Acknowledgments

Our thanks are due to Mr. A. B. Lloyd for supplying a number of materials, and for arranging a valuable discussion at the works of F. H. Lloyd and Co., Ltd., between the Company's staff and themselves; to Professor C. E. Tilley and Dr. N. M. F. Henry for arranging the petrographic examinations; to Mr. M. E. Hargreaves for assistance with the X-ray work; and to William Jessop and Sons, Ltd., for the supply of analysed steel specimens. We also acknowledge the skill of Mr. J. R. Goldwin, who constructed most of the fused silica apparatus.

We are indebted to the Department of Scientific and Industrial Research for a Maintenance Allowance to one of us (D.V.A.), during the tenure of which this work was carried out.

References

1. Mould Surface Committee of the American Foundrymen's Association, 1948. Preprint No. 48-29.
2. A. H. DIERKER: *Transactions of the American Institute of Mining and Metallurgical Engineers*, 1930, vol. 90, p. 83.
3. P. L. GOODALE: *Transactions of the American Foundrymen's Association*, 1930, vol. 38, p. 471.
4. S. G. JONES: *American Foundryman*, 1948, vol. 13, p. 139.
5. J. B. CAINE: *Transactions of the American Foundrymen's Association*, 1945, vol. 51, p. 647.
6. S. H. LJUNGGREN: *Jernkontorets Annaler*, 1945, vol. 129, No. 8, p. 457.
7. W. VASKA: *Giesserei*, 1942, vol. 29, No. 18, p. 311.
8. M. ARDENNE and K. ENDELL: *Giesserei*, 1943, vol. 30, No. 1, p. 6.
9. D. M. BACHELOR: *Foundry*, 1947, vol. 75, p. 80.
10. A. B. LLOYD: *Proceedings of the Institute of British Foundrymen*, 1948, vol. 41, p. A107.
11. C. W. BRIGGS: "The Metallurgy of Steel Castings," p. 402. New York and London, 1946: McGraw-Hill.
12. Metals Handbook, p. 20, 1948, American Society for Metals.
13. A. I. KRYNITSKY: *Metals and Alloys*, 1933, vol. 4, p. 79.
14. C. KEMBALL: *Transactions of the Faraday Society*, 1946, vol. 42, p. 526.
15. R. F. SARJANT: Third Report of the Steel Castings Research Committee, p. 133, 1938, The Iron and Steel Institute.
16. K. W. SACK and W. J. REES: *Ibid.*, p. 130.
17. C. W. BRIGGS and R. A. GEZELIUS: *Transactions of the American Foundrymen's Association*. 1935, vol. 42, p. 274.
18. V. PASCHKIS: *Transactions of the American Foundrymen's Association*, 1947, vol. 55, p. 74.
19. C. L. LUCKS, O. L. LINEBRINK, and K. L. JOHNSON: *Ibid.*, p. 62.
20. H. W. DIETERT, E. J. HASTY, and R. L. DOELMAN: *Ibid.*, p. 84.
21. H. W. RUSSELL: *Journal of the American Ceramic Society*, 1935, vol. 18, p. 1.
22. H. A. SCHWARTZ: *Transactions of the American Foundrymen's Association*, 1945, vol. 53, p. 159.
23. V. KONDIC and N. J. KOZLOWSKI: *Journal of the Institute of Metals*, 1949, vol. 75, p. 665.
24. E. T. LINACRE: Battersea Communication, No. 13, 1947, British Iron and Steel Research Association.
25. P. KOZAKEVITCH: *Révue de Métallurgie*, 1949, vol. 46, p. 505.

CORRESPONDENCE ON PAPERS

Correspondence on the Paper—

ELECTRON MICROSCOPE STUDY OF QUENCHED AND TEMPERED STEEL*

By J. Trotter and D. McLean

Dr. **K. H. Jack** (Department of Chemistry, King's College, Newcastle-upon-Tyne): The authors' results offer considerable support for a proposed mechanism of martensite tempering[1] which is based on direct X-ray evidence obtained at the Crystallographic Laboratory, Cambridge during the early part of 1949. A detailed account of this work will be published shortly but it is perhaps appropriate that the main features should be outlined here.

Adopting the nomenclature used by Trotter and McLean, the loss of tetragonality of martensite during stage (*a*) is due to the coherent precipitation of a close-packed hexagonal iron carbide which it is proposed should be named ϵ-iron carbide, or ϵ-Fe_2C, because of its structural similarity with ϵ-Fe_3N. ϵ-iron carbide is the non-cementite precipitate suggested by previous workers, but it is formed from martensite as a transition phase in which the Laue condition for X-ray reflection is obeyed preferentially in a direction normal to the (101) lattice planes. According to Geisler[2] the particles of a coherently precipitated phase are usually very small, and since they are strained to 'fit' with the atomic sites of the matrix they are orientated with respect to the matrix and commonly produce one-dimensional or

MS received 13th February, 1950.

* *Journal of The Iron and Steel Institute*, 1949, vol. 163, pp. 9–13. Previous correspondence appeared in the *Journal of The Iron and Steel Institute*, 1950, vol. 164, p. 288.

two-dimensional X-ray diffraction effects. A coherent precipitate with its surrounding field of strained matrix offers greater resistance to slip than an incoherent dispersed precipitate. Apart from the one-dimensional X-ray effects given by ϵ-iron carbide, its formation is accompanied by pronounced broadening of the ferrite X-ray powder reflections. Indeed, the line breadths greatly exceed those of the original martensite pattern. The unit cell dimensions of ϵ-iron carbide are

$$a = 2{\cdot}73\text{Å}. \quad c = 4{\cdot}33\text{Å}. \quad \left(\frac{c}{a} = 1{\cdot}58\right)$$

and are similar to those of the supposed 'Fe_3N' reported by Heidenreich, Sturkey, and Woods.[3]

The spacing of the (101) lattice planes is almost identical with that of the (101) planes of martensite, so that a simple orientation relationship between the two phases is probable. Although diffusion of carbon atoms must accompany the first stage of tempering, the formation of an orientated close-packed hexagonal structure from the original body-centred tetragonal structure can occur by quite small movements in the [101] direction of alternate (101) planes of iron atoms. The evidence that stage (*a*) of martensite tempering is similar to other age-hardening systems is therefore complete, and the increase in hardness which is observed in the first stage of steel tempering[1] is to be expected. ϵ-iron carbide forms the carbon-rich extreme of the previously reported[5] series of close-packed hexagonal ϵ-iron carbonitrides at their lower interstitial-atom concentration limit, $Fe_3(C, N)$. A similar iron carbide, Fe_2C, has been described by Hofer, Cohen, and Peebles[6] as the carbon-rich extreme of the same carbonitride series at their upper interstitial-atom concentration limit, $Fe_2(C, N)$.

During the third stage of steel tempering (stage (*b*) of the martensite decomposition), ϵ-iron carbide transforms to give a fine dispersion of very thin platelets of strained and slightly distorted cementite, still coherent with the matrix and with the plane of the plate parallel with the (001) lattice plane of the cementite structure. The observed X-ray diffraction pattern is markedly different from that of crystalline cementite since the Laue condition is fulfilled completely only in directions parallel with the (001) planes and is absent in the [001] direction. Included among the strongest of the observed reflections are the previously unidentified reflections observed on X-ray photographs of tempered martensite by Arbusov and Kurdjumov[7] and ascribed by them to a new iron carbide. With increasing tempering times or at higher temperatures the gradual growth and recrystallization of the distorted cementite platelets are accompanied by loss of coherency and reduction in lattice strain. Some sharpening of the ferrite reflections is observed quite early in stage (*b*), but the normal crystalline cementite pattern is not observed even after some weeks at 350° C. Detailed comparison of these X-ray results with the electron microscope observations is not possible since the transformations depend both on time and temperature and the tempering times given by Trotter and McLean are in general much shorter than in my own work. It is quite clear, however, that the two successive stages of martensite tempering are:

Stage (*a*), martensite → ϵ-iron carbide
Stage (*b*), ϵ-iron carbide → cementite.

The iron atom arrangement of the cementite structure is not greatly different from that of the close-packed hexagonal carbide, and the change from the latter to the former involves only very small movements of one third of the iron atoms.

Not only does the proposed mechanism account for the changes in hardness which occur on tempering martensitic steels, but it also offers a quantitative explanation for observed changes in specific volume.

AUTHORS' REPLY

Mr. **Trotter** and Mr. **McLean** (National Physical Laboratory) wrote: Dr. Jack reports what appears to be convincing evidence about the changes during the tempering of martensite and, as he indicates, there is substantial agreement between his conclusions and our own. In particular, there is now evidence from four separate sources that platelets form at one stage during tempering; in addition to the present paper and Dr. Jack's work, evidence has been reported by Crafts and Lamont[8] and by Calnan and Clews.[9] In view of the suspicion with which the electron microscope is still regarded by some metallurgists, it is perhaps worth pointing out that these particles were first detected, in residues and *in situ*, by this instrument. In our paper it was provisionally supposed that the platelets were the non-cementite phase. At that time only one precipitate phase different from normal cementite had been reported, but now that X-ray work has established the occurrence, below 350° C., of platelets of a slightly distorted cementite structure, it seems certain that the platelets we observed after tempering at 250° C. (Fig. 6) are to be identified with these platelets. The finer particles we observed after tempering at 170° C. (Fig. 5) are possibly to be identified with Dr. Jack's coherent precipitate of hexagonal iron carbide.

In our paper it was also deduced that the fine precipitate at 170° C. was coherent (continuous) with the matrix, from the fact that the platelets, which we supposed to be the first non-coherent (detached) precipitate, appeared subsequently. Dr. Jack, however, considers the platelets to be coherent. It would be interesting to know on what evidence this is based.

The martensite line broadening referred to by Dr. Jack may have significant contributions from causes other than direct lattice strain such as the variation in composition from the low-carbon content around a precipitate, to the higher content where precipitation has not yet occurred, and the residual tetragonality varying with carbon content. These contributions will change as tempering progresses.

REFERENCES

1. K. H. Jack: Ph.D. Thesis, Sept. 1949, University of Cambridge.
2. A. H. Geisler: *Metals Technology*, Technical publication No. 2436
3. R. D. Heidenreich, L. Sturkey, and H. L. Woods: *Journal of Applied Physics*, 1946, vol. 17, p. 127.
4. D. P. Antia, S. G. Fletcher, and M. Cohen: *Transactions of the American Society for Metals*, 1944, vol. 32, p. 290.
5. K. H. Jack: *Proceedings of the Royal Society*, 1948, series A, vol. 195, p. 41.
6. L. J. E. Hofer, E. M. Cohn, and W. C. Peebles: *Journal of the American Chemical Society*, 1949, vol. 71, p. 189.
7. M. Arbusov and G. Kurdjumov: *Journal of Physics*, U.S.S.R., 1941, vol. 5, pp. 101–108.
8. W. Craft and J. L. Lamont: *Metals Technology*, Technical publication No. 2439, 1948, Sept.
9. E. A. Calnan and C. J. B. Clews: Symposium on Metallurgical Applications of the Electron Microscope. Monograph and Report Series, No. 8, 1950, The Institute of Metals.

The Distribution of Temperature in Ingot Moulds and Its Relation to Ingot Structure

By I. M. Mackenzie and Andrée Donald

SYNOPSIS

A 3-ton ingot of mild steel fully killed with silicon and aluminium was sectioned, and the sub-surface structure was examined by sulphur printing and macro-etching. The effect of convection currents in the superheated metal giving rise to banding of dendrites near the surface is discussed. An experiment to show the effect of 'overkilling' with aluminium and silicon in producing axial porosity is described.

Experiments to determine the changing temperature distribution within the ingot mould wall are described, and the results obtained are used in a calculation of the rate of heat transfer to the mould. It is shown that the rate of heat transfer is initially at a maximum value which may exceed 2000 cal./sq. cm./min., the rate decreasing to about one-tenth of this value within 10 minutes. A graphical method of successive approximations is used to calculate the rate of solidification of the ingot. It is shown that while the thickness of the solid skin may be given approximately by an expression of the form : skin thickness = constant $\sqrt{\text{time}}$, this function is only empirical and it does not hold over the first few minutes after teeming.

The factors controlling the rate of heat transfer to the mould are discussed with particular reference to the early separation of the ingot skin from the mould wall. The experimental data and the results of the approximate calculations are made the basis of hypotheses of the mechanism of solidification and of the formation of ingot cracks. It is suggested that cracks are most likely to form during the first few minutes after teeming because of the rapid expansion of the mould and the consequent stretching of the newly formed ingot skin. A postulated mechanism is shown to explain the observed effects of superheat, teeming speed, and sulphur content on the incidence of cracking.

Introduction

INGOT surface quality is a subject attracting much attention at the present time, and numerous investigations are being carried out to ascertain the cause of defects such as cracks, double skin, blowholes, etc. As skin defects are produced by conditions prevailing during and immediately after teeming, the elucidation of these problems awaits a more complete explanation of the effects of superheat and turbulence on the structure of the ingot, and a determination of the rate of abstraction of heat from the steel, and of the origin of stresses in the newly formed skin.

As part of an investigation into the mechanism of ingot cracking, experimental work has been carried out on some of the controversial problems. The principal questions to be answered were :

(i) What is the rate of transfer of heat from the ingot to the mould, and how does it vary with time

(ii) Is the separation of the ingot from the mould continuous or discontinuous, and what is the extent of separation when the outer skin of the ingot is solidifying

(iii) What is the structure of the ingot immediately below the surface and why does the mode of crystallization change from the skin zone to the columnar zone ?

The condition during the early stages of solidification was investigated by examining the structure of experimental ingots and by following the change in temperature distribution within the mould. From a knowledge of the temperature gradients in the mould wall it was possible to make an approximate determination of the rate of heat transfer from the ingot, and of the mould expansion. Knowing the rate of abstraction of heat, it was possible to estimate the rate of solidification and the temperature drop between the ingot and the mould.

EXAMINATION OF INGOT STRUCTURE

To obtain evidence of the condition during the early stages of solidification, the structure of three experimental ingots was examined. As the main features of the ingots were found to be similar, one ingot only was studied in detail. This ingot was top-run in a mould similar to that used for the experiments on mould temperatures, and was of electric furnace steel of composition : C 0·23%, Si 0·36%, S 0·018%, P 0·030%, Mn 0·79%, Ni 0·28%, Cr 0·07%. To ensure that there could be no gas evolution during solidification, 1 lb. of aluminium per ton of steel was added to the ladle. Unfortunately no teeming temperature was obtained.

The ingot was sectioned along its longitudinal axis. One half was used for sulphur printing and an analysis survey, and the other was cut up for micro-examination, as shown in Fig. 1. The degree of segregation was normal but the axial zone was found to be porous, as is shown on the sulphur print (Fig. 2). Porosity could be distinguished from sulphur segregation by examination under a low-power microscope (Fig. 3*a*). It was suspected that this abnormal porosity had been caused by overkilling with aluminium, and this effect was demonstrated by casting two 9-lb. H.F.-furnace ingots with the same

Manuscript received 21st September, 1949.

Mr. Mackenzie and Mrs. Andrée Donald are at Messrs. Colvilles, Ltd., Motherwell.

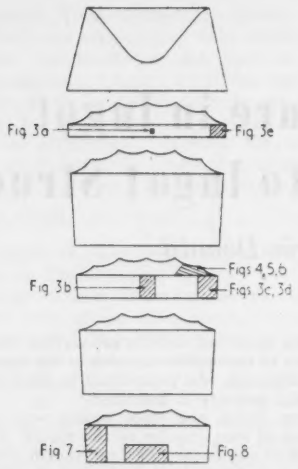


Fig. 1—Sectional diagram of 3-ton ingot

composition as the electric-furnace-cast ingot but an aluminium addition equivalent to 1 lb. per ton was made to one of them. The overkilled ingot was found to be axially porous, while the other was perfectly solid. It is possible that the more completely deoxidized metal was more viscous at the liquidus temperature, and that there was less efficient feeding of metal into the axial zone of the aluminium-killed ingot.

To investigate the primary crystal structure, sections were etched with Stead's reagent. Figures 3*b–d* show typical fields from the central, columnar, and skin zones respectively. The crystals in the central zone were large, equiaxed, and randomly orientated (Fig. 3*b*). The columnar zone varied from the bottom to the top of the ingot. At the bottom the crystals were very long and were all parallel (Fig. 3*c*). The zone extended about 4 cm. from the surface, and the transition from columnar to equiaxed crystals was abrupt. Higher in the ingot the crystals were still elongated but their orientation was more random (Fig. 3*e*). There was no definite boundary between the columnar and equiaxed zones at the top of the ingot. The skin zone was composed of small dendrites which tended to have the same preferred orientation as the columnar zone; however, the growth of these dendrites had been checked so that they appeared to be arranged in bands parallel to the ingot surface (Fig. 3*d*). The bands, which were most numerous and more widely spaced at corners and which were particularly pronounced near the bottom of the ingot, commonly marked the boundary of the 'skin zone,' but were also found well inside the columnar zone (Fig. 4). Zones where the bands were very close together or superimposed appeared as white lines on a sulphur print or macro-etch (Figs. 5 and 6). Similar banding in a bottom-run shell steel ingot has been studied by Binnie,[1] who reached the following tentative conclusions:

(i) The banding did not bear any relationship to the crystal structure
(ii) There was no appreciable change in composition on passing across the banded zones
(iii) There were fewer sulphide inclusions to be seen in bands appearing white on a sulphur print
(iv) The banding could be caused by periodic variations in the rate of crystallization.

The banding was probably the result of the combined effect of forced convection and superheat. As the steel ran into the mould it would set the liquid in motion as shown in Fig. 11. A flow of metal against the solidifying surface would check the growth of the columnar crystals, and when the flow was streamlined, solidification would be inhibited as long as the liquid was superheated. If the flow was turbulent there would be intervals during which solidification took place alternating with periods during which solidification was inhibited, so that the primary structure presented a banded appearance.

At the corners there were relatively quiescent zones in which solidification proceeded with less interruption. Thus, a vertical section through the bottom corner (Fig. 7) shows a thin banded zone formed while the flow was more turbulent. When the liquid level had risen sufficiently for the streamlined current to be set up, solidification proceeded with little interruption up to the boundary of the streamlined flow, where the structure shows numerous closely spaced bands formed when fresh superheated liquid was being carried against the skin. At the upper surface of the liquid the conditions must have been similar to those at the bottom corner, and the outer layer of metal would have commenced to solidify immediately. Owing to the turbulent flow of the superheated liquid this layer was heavily banded (Fig. 3*d*). However, as the liquid level rose, the portion of the skin which had been forming in the upper, quiescent zone was subjected to the steady stream of hot metal so that solidification was checked for a considerable period, giving rise to the thin zone of metal, low in sulphur and carbon, by an action comparable to the movement of liquid in a rimming steel. At the corners of the duodecagon, solidification was never completely checked but continued at a reduced rate so that separate bands were formed (Fig. 4).

By the time the liquid level had reached the upper portion of the mould a considerable quantity of heat had been abstracted from the liquid, so that it was not sufficiently superheated to check solidification. Thus, few bands are seen near the ingot head (Fig. 3*e*), but a section from the bottom of the ingot near the point where the teeming stream struck the stool shows numerous bands which appear to follow the direction of flow of the liquid steel (Fig. 8). Individual crystals passed through the bands. The banding is evidence that solidification was inhibited as long as the liquid metal was superheated, because of the turbulent flow produced by the impact of the teeming stream, and shows that the greater part of the superheat must have been removed while the metal was still teeming. This agrees with the results of experiments carried out by Tageev and Gulyaev,[2] in which the temperature of the steel was determined by thermocouples.

MOULD WALL TEMPERATURES

The variation in temperature within mould walls has been investigated by Matuschka,[3] by the Hetero-

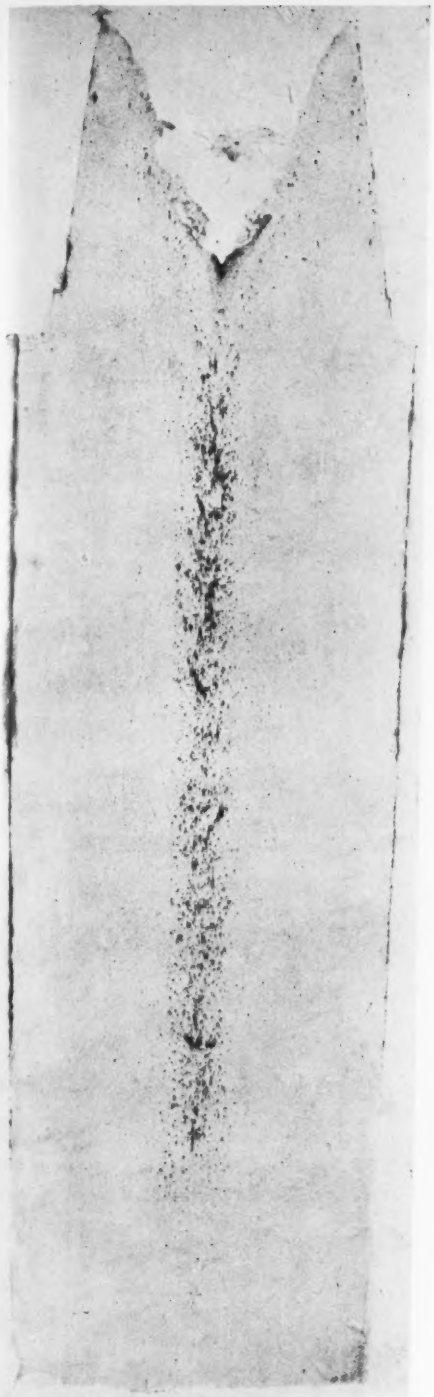


Fig. 2—Sulphur print from 3-ton ingot showing axial porosity

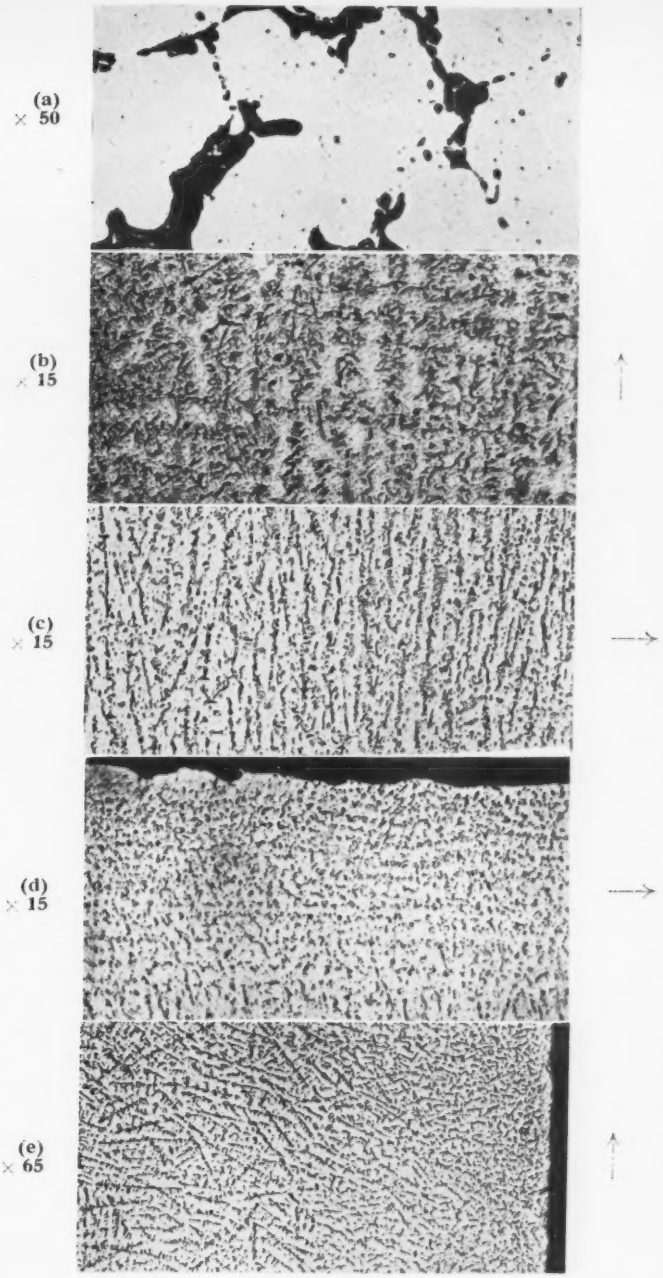


Fig. 3—Three-ton ingot : (a) axial porosity, (b) central zone, (c) columnar zone, (d) skin zone with banding parallel to surface, (e) columnar crystals near top of ingot. (b), (c), (d) and (e) treated with Stead's reagent

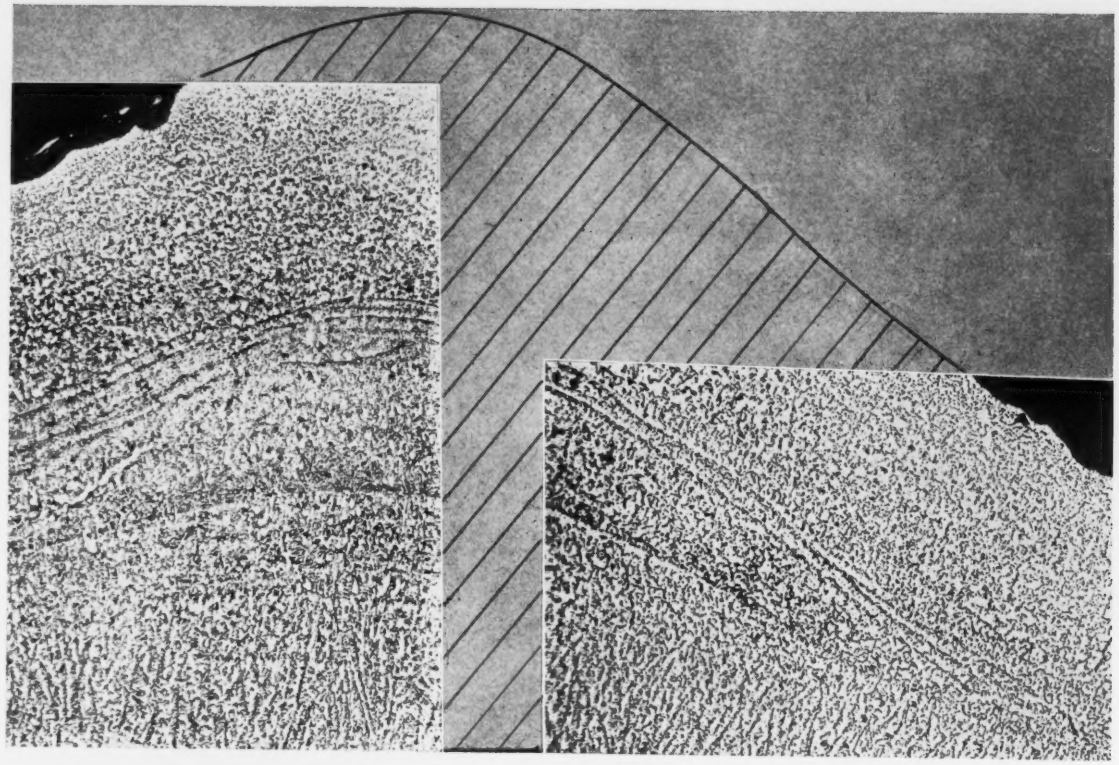


Fig. 4—Fields from an ingot corner showing bands branching and increasing in thickness. Horizontal section, etched with Stead's reagent × 6·5

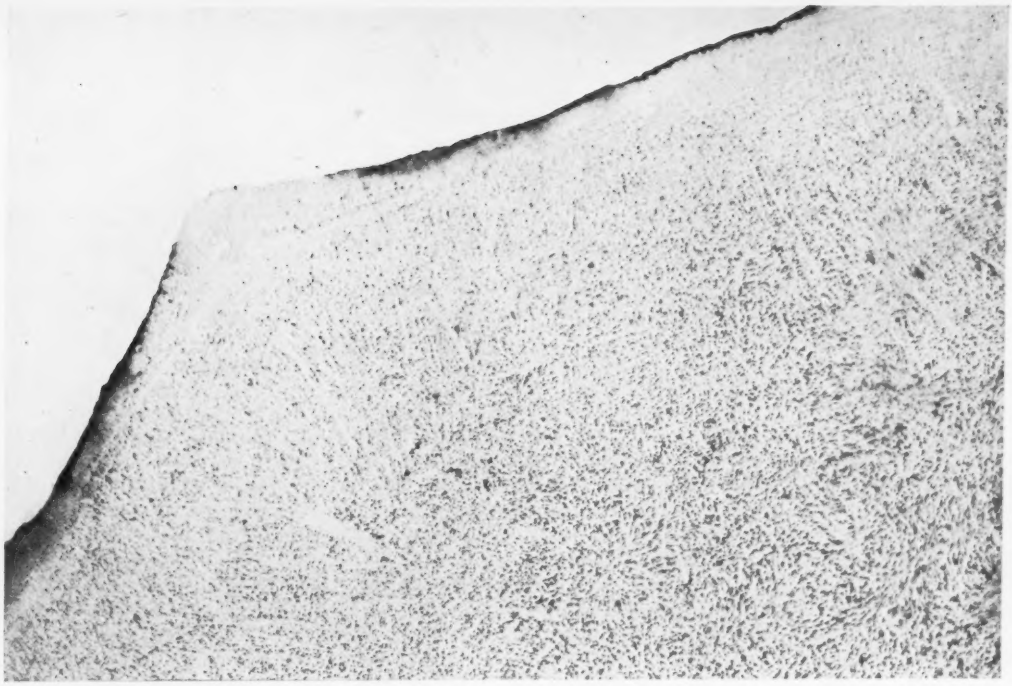


Fig. 5—Sulphur print from horizontal section through ingot corner, actual size

Fig. 6—Macro-etch of horizontal section through ingot corner, actual size

Fig. 7—Vertical section of bottom corner of ingot showing double banded zone. Etched with Stead's reagent × 3

Fig. 8—Section of bottom of ingot near point where teeming stream struck stool. Etched with Stead's reagent × 6·5

Fig. 9—Ingot cracking and surface defects. Etched with Stead's reagent × 3·5

Fig. 10—Section through crack showing junction of dendrites × 6·5

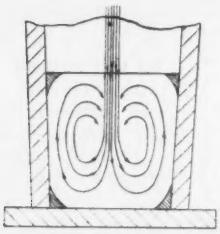


Fig. 11—Diagram of forced convection currents in top-run ingots

geneity of Steel Ingots Committee,[4] and by Tageev and Gulyaev.[2] It was found that the interior temperature rapidly reached a maximum, dropped suddenly, and then increased slowly as the whole thickness of the wall was heated. The drop in temperature was considered to be caused by sudden separation of the ingot and mould surfaces.

Determinations of mould-wall temperature were carried out by Jackson and others,[5] and experimental and calculated results compared. However, no results were shown for the temperature distribution during the first 10 min. after teeming, and the ingot surface structure is known to be determined by conditions prevailing at this time.

Experiments designed to amplify these conclusions and to provide sufficient data for the determination of the rate of heat transfer to the mould were carried out, with an arrangement similar to that employed by Matuschka, on a 3-ton duodecagonal inverted mould with a bricked hot-top. This type was chosen because its approximately annular transverse section simplified some of the calculations, and because the change in ingot structure at a corner could be studied.

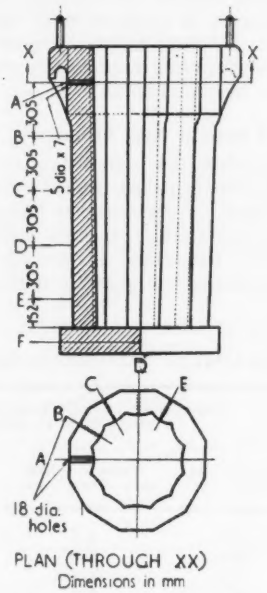


Fig. 12—Position of thermocouples in 3-ton duodecagonal mould

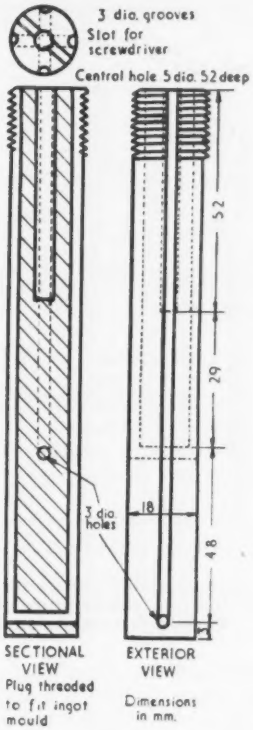


Fig. 13—Positioning arrangement for thermocouples in mould wall

Experimental Procedure

Holes of 18 mm. dia. were drilled through the mould wall at approx. 15, 46, 76, 107, and 122 cm. from the bottom. The holes were at the middle of the faces of the fluted duodecagon, staggered round the mould in a spiral (Fig. 12). Plugs to hold three Pt/Pt–Rh thermocouples were machined from the same cast iron as the mould (Fig. 13), and were screwed into the wall so that their ends were exactly flush with the interior surface. The two thermocouples nearest the interior surface were led down grooves at the sides of the plug, and the junctions were jammed in holes drilled parallel to the surface to minimize interference with the flow of heat along the axis of the plug. A third couple was sunk in a hole drilled in the end of the plug. The junctions were 3, 51, and 80 mm. from the inner surface of the mould. Plugs, made to take only the inner couple, were used to investigate the variation in the interior temperature from the top to the bottom of the mould. Temperatures obtained with both types of plug were similar, so that any errors due to the presence of the holes must have been small. Thermocouples were also tamped into shallow holes drilled in the exterior of the mould near each plug. Precautions were taken to minimize the loss of heat along the thermocouple wires, which was suspected to be a source of error in Matuschka's experiments.

The e.m.f. of each thermocouple was measured with moving-coil millivoltmeters accommodated on a specially designed bench to minimize the effect of

Fig. 9—Ingot cracking and surface defects. Etched with Stead's reagent × 3·5

Fig. 10—Section through crack showing junction of dendrites × 6·5

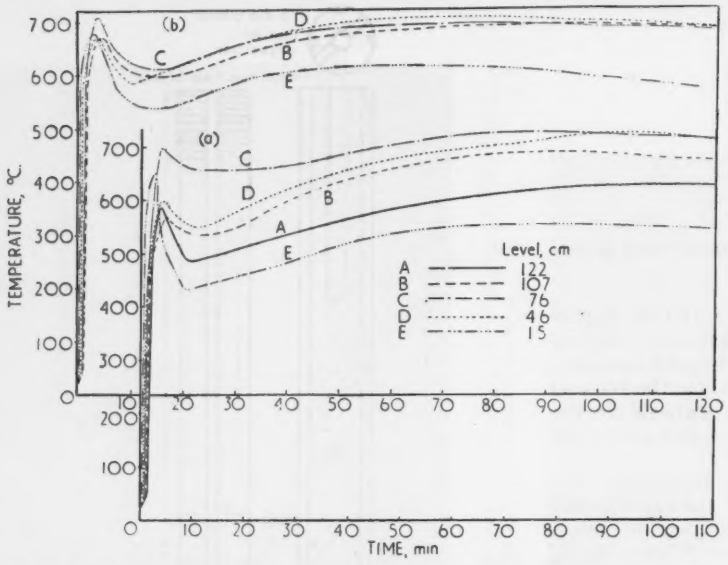


Fig. 14—Time/temperature curves for thermocouples 3 mm. from interior mould surface, (a) temperature of metal in ladle 1610° C., hot top 1550° C., (b) temperature of metal in ladle 1640° C.

vibration. Multipoint switches were used for couples where frequent readings were not required.

The experiments were carried out on low-alloy and plain carbon steels made in a 10-ton electric-arc furnace. The steel was direct-poured through fireclay nozzles of 1½ in. dia., the experimental mould always being filled first. The mould, set away from the remainder of the cast in a sheltered part of the shop, was not dressed but was thoroughly brushed inside before each experiment. It was always at atmospheric temperature when used, and was set on a cast iron stool 5 in. thick. The temperature of the steel was measured in the ladle and in the moulds immediately after teeming, using silica-sheathed thermocouples ; the instant when the first metal entered the mould being taken as zero time. The millivoltmeters were read at intervals of 30 sec. for the first 10 min., and thereafter, at less frequent intervals, until stripping.

In the first series of experiments temperatures were measured at all six interior positions and at three levels at the exterior. After a preliminary trial two sets of readings were obtained. Time/temperature curves for each thermocouple are shown in Figs. 14*a* and *b*. All the interior couples showed initial maxima. The time intervals between the beginning of the temperature rise and the maximum reading are shown in Table I. The highest temperature was recorded for the middle couple. As the initial temperature changes are less marked and occur later further from the inner surface, the maximum surface temperature will be reached after times shorter than those in the Table.

In the second series of experiments the temperature gradients through the mould wall were determined. Results obtained for the 46- and 107-cm. levels are shown in Figs. 15 and 16. The time/temperature curves are displaced along the time axis at distances proportional to the distances of the couples from the inner mould surface. Isotime lines drawn through the four curves show the temperature gradients, the estimated temperature of the inner mould surface (θ_m) is shown by a dotted line.

These temperature gradients were of a different shape from those shown by Matuschka.[3] In the discussion to his paper it was pointed out that as long as the mould wall is heating, the curves might be expected to be concave upwards. It seems likely that the external mould temperatures obtained by Matuschka with couples spot-welded to the cast iron were low, because of conduction of heat down the couple wires. By tamping the exterior couples into shallow holes this error was greatly reduced in the present series of experiments.

Calculation of Rate of Heat Transfer

During the first few minutes after teeming the greater part of the heat lost from the steel was stored in the mould wall. As the exterior temperature of the mould rose above that of its surroundings, heat was dissipated from the mould surface at an increasing rate ; the rate of heat loss when the mould temperature

Table I

TIME INTERVALS BETWEEN ZERO TIME AND MAXIMUM TEMPERATURE

Distance of Couple from Bottom, cm.	Experiment 1—Ladle Temp. 1610° C. Time to Teem 2 min.			Experiment 2—Ladle Temp. 1640° C. Time to Teem 1½ min.		
	Initial Max. Temp., °C.	Time of Initial Max. Temp., min.	Final Max. Temp.$_f$ °C.	Initial Max. Temp., °C.	Time of Initial Max. Temp., min.	Final Max. Temp., °C.
15	650	2·5	552	680	2·5	620
46	600	3·5	730	670	3·0	710
76	700	4·5	730	710	3·5	720
107	570	5·0	690	672	4·0	700
122	590	3·5	630	...	...	640

had reached its maximum could be estimated from the temperature drop through the wall. The maximum temperature reached by the exterior surface of the mould was about 500° C., and the rate of dissipation of heat was then about 60 cal./sq. cm./min. As the heat was removed from the mould principally by convection, the rate of loss must have been approximately proportional to the surface temperature.

At the central portion of the mould there would be a negligible flow of heat in the longitudinal and circumferential directions. The heat transferred from unit area of ingot surface would heat a volume of mould opposite it or would pass through this volume and be dissipated from the exterior of the mould. The heat stored in the volume of mould wall may be estimated from the temperature distribution experimentally determined. Assuming the mould to be a cylinder, the volume corresponding to 1 sq. cm. of ingot surface is that represented by the truncated wedge shown in Fig. 17. The volume in cubic centimetres of this wedge between the internal surface and a distance y cm. from the interior is :

$$y\left(1+\frac{y}{2R}\right)$$

The heat content of the wedge may be determined by plotting the temperature against the value $y\left(1+\frac{y}{2R}\right)$ for all the values of y. The area under the curve is proportional to the increase in heat content of the wedge, the constant of proportionality being the product of the specific heat and the specific gravity. The values assumed for these quantities are given on p. 24. Curves of temperature/$y\left(1+\frac{y}{2R}\right)$ for each minute after the commencement of teeming, plotted for the 107-cm. level are shown in Fig. 18. The areas between the curves and the abscissae at the initial temperature were measured with an Amsler planimeter. The heat stored in the wedge-shaped element of the mould wall by the end of each minute was then plotted against time (dotted line *C*, Fig. 19). The gradient of this line gave the instantaneous rate of increase in heat content in calories per minute (dotted line *D*, Fig. 19). For the estimation of the rate of heat transfer from the ingot to the mould a correction must be made for the quantity of heat dissipated from the mould exterior to give the full lines in Fig. 19. The area under the full line *D* in Fig. 19 is proportional to the quantity of heat transferred from unit area of mould surface. This is shown by the full line *C* in the same Figure. During the first 15 min. only a small fraction of the

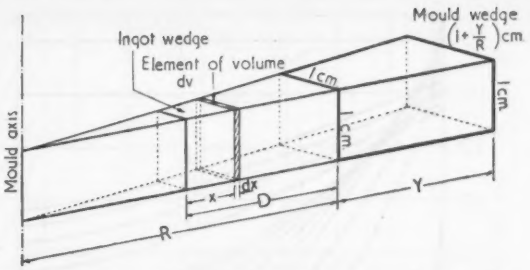


Fig. 17—Element of mould wall and ingot skin considered in calculations of rate of heat transfer from ingot to mould and of ingot skin thickness

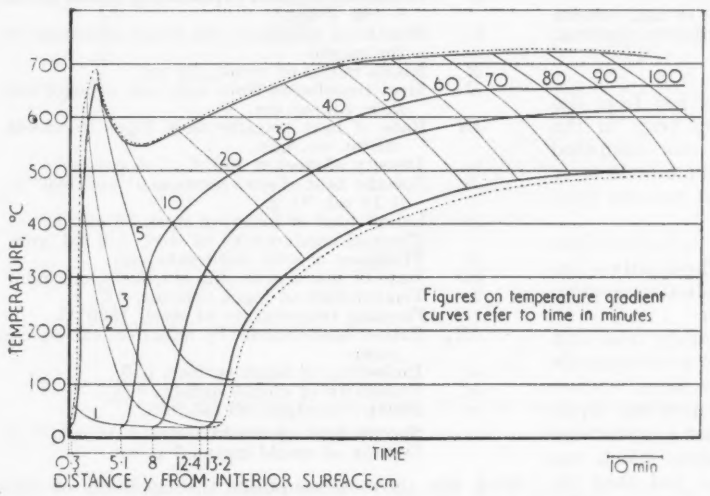


Fig. 15—Temperature distribution within the mould wall : 46-cm. level

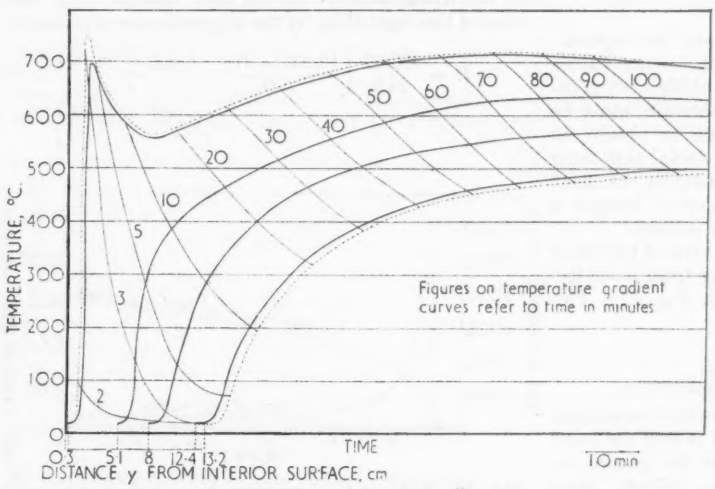


Fig. 16—Temperature distribution within the mould wall : 107-cm. level

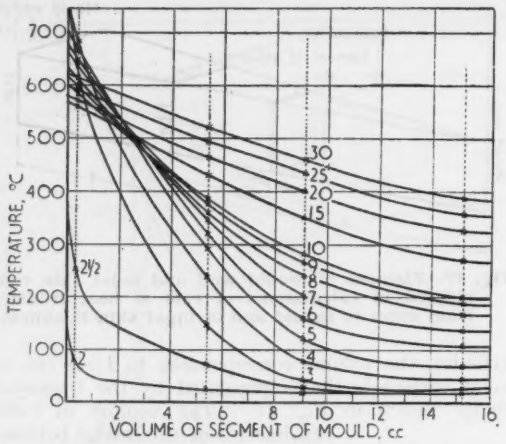


Fig. 18—Determination of heat content of unit volume of mould wall by temperature distribution plotting: 107-cm. level

heat transferred from the ingot was lost from the mould. Thus, up to this time any error in the estimate of the rate at which heat was dissipated from the mould exterior will introduce little error into the determination of rate of heat transfer from the ingot.

The main sources of error are likely to be the values assumed for the specific heat and for the density of the cast iron, and the approximation involved in treating the duodecagonal mould as a cylinder.

The variation in the rate of heat transfer from unit area of the ingot surface was found to be comparable for all experiments. A point on the mould surface received heat at an increasing rate until the liquid level reached it, when the rate of heat transfer rose almost instantaneously to a maximum, which was usually over 2000 cal./sq. cm./min., and then decreased rapidly, falling to about 200 cal./sq. cm./min. 10 min. after teeming.

Calculation of Rate of Solidification

The results may be used to calculate the approximate rate of solidification of the ingot. Since values for the physical constants of the steel at high temperature, for which the data are very uncertain, must be assumed, no attempt has been made to obtain an exact solution for the thickness of the solid skin from the function relating it to the quantity of heat abstracted and the rate of heat transfer; instead a method of successive approximation is used.

The heat transferred through unit area of the ingot surface may be considered as coming from a wedge-shaped volume of steel as shown in Fig. 17. This heat is derived from three sources:

(i) Superheat on liquid steel
(ii) Latent heat of solidification
(iii) Heat abstracted from the solid skin.

As is shown by the banding, there is little superheat on the metal by the time the mould is half full, and the effect of superheat may therefore be ignored for calculation of skin thickness at the 107-cm. level. The interface between the solid and liquid portions of the steel will be at the melting point (about 1520° C. for a steel with 0·2% of carbon). As heat is flowing from the solidifying surface there will be a temperature gradient in the solid skin which will be related to the rate of solidification. To produce this gradient the skin must be cooled. At the exterior surface of the skin the temperature gradient may be determined from the rate of heat transfer to the mould. For an approximate calculation it is reasonable to assume that the change in temperature gradient is constant across the skin, and that the specific heat and thermal conductivity are independent of temperature.

The symbols employed and the values assumed for the physical constants are as follows:

θ_m	Temperature of mould interior, ° C.
y	Distance through mould wall from inner surface, cm.
Y	Thickness of mould wall, 13·2 cm.
α	Coefficient of linear expansion of mould metal, $0{\cdot}106 \times 10^{-4}$
b	Fractional change in the linear dimension of the mould
R	Inside radius of mould, 28 cm.
H	Heat transferred from unit area of ingot surface, cal./sq. cm.
δH	Rate of heat transfer from ingot to mould, cal./sq. cm./min.
G	Density of steel at 400° C., 7·5 g./c.c.
K	Specific heat of steel between 0° and 600° C., 0·18 cal./°C./g.
λ	Latent heat of fusion of steel, 55 cal./g.
c	Thermal conductivity of steel, 3·6 cal./min.
D	Thickness of solid ingot skin, cm.
δD	Rate of increase in skin thickness, cm./min.
θ_s	Temperature of ingot exterior, ° C.
z	Freezing temperature of steel, 1520° C.
δH_R	Rate of heat transfer by radiation, cal./sq. cm./min.
e_1	Emissivity of ingot surface, 0·5
e_2	Emissivity of mould surface, 0·5
σ	Stefan's constant, 83 cal./min.
	Specific heat of mould metal, 0·14 cal./°C./g.
	Density of mould metal, 7 g./c.c.

With the above assumptions the thickness of solid skin at any time can be shown to be related to the total quantity of heat abstracted from the wedge and to the instantaneous rate of heat transfer from unit area of the ingot skin, by the approximate expression:

$$H = \frac{KG\lambda D^2}{24R}\left[\frac{12(2R-D)}{KD} + \frac{G(8R-3D)\delta D}{c} + \frac{(4R-D)\delta H}{\lambda c}\right]$$

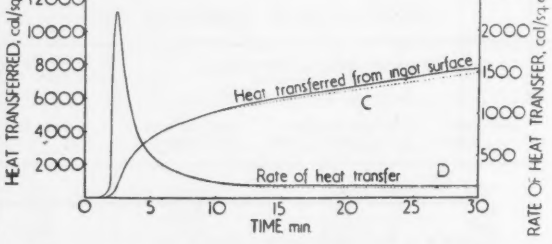


Fig. 19—Rate of heat transfer from ingot to mould: 107-cm. level

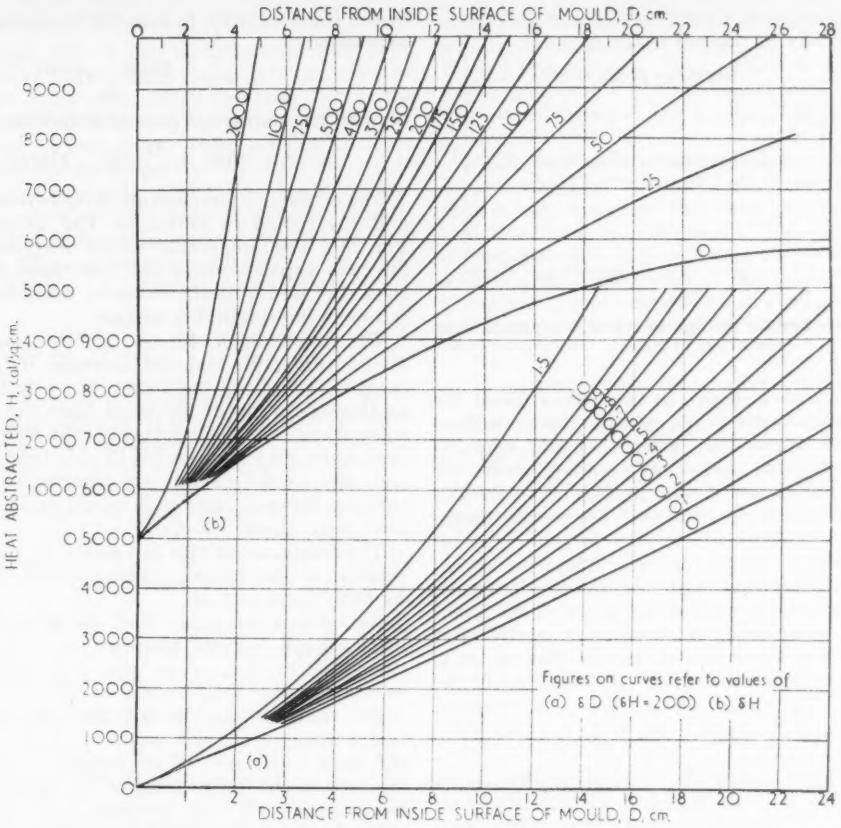

DISTANCE FROM INSIDE SURFACE OF MOULD, D cm.
HEAT ABSTRACTED, H, cal/sq cm.
Figures on curves refer to values of
(a) δD (δH = 200) (b) δH
(a)
(b)

Fig. 20—Nomograms for ingot skin thickness determination from heat transfer data : (*a*) when $\delta H = 200$ (*b*) special case for 1st approximation $\delta D = \frac{\delta H}{412}$

or with the numerical constants included :

$$H = 0{\cdot}307D^2\left[\frac{24(56 - D)}{D} + 0{\cdot}75(224 - 3D)\delta D + \frac{(112 - D)\delta H}{550}\right]$$

The derivation of this formula is shown in the Appendix.

Values of D may be determined for experimental values of H and δH from nomograms for different values of δD (*see* Figs. 20*a* and *b*). For the first approximation, δD is not known and it is therefore assumed that the temperature gradient through the skin is constant. Thus δD is assumed to be equal to :

$$\frac{\delta H}{G\lambda} = \frac{\delta H}{412}$$

From the graph of the first approximation of D/time approximate values of δD were determined. When these values of δD were used a closer approximation to D was obtained. The calculation was repeated for successive approximations to δD until

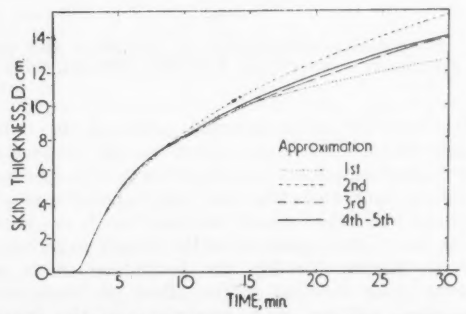


Fig. 21—Ingot-skin-thickness/time after commencement of teeming showing successive approximations : 107-cm. level

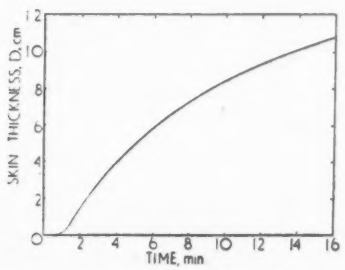


Fig. 22—Ingot-skin-thickness/time after commencement of teeming : 46-cm. level

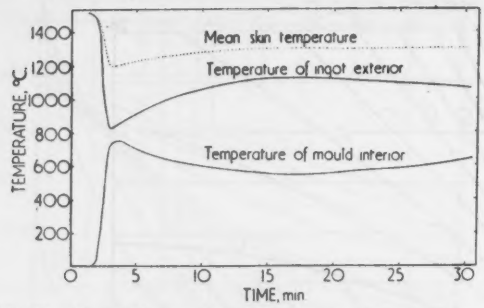


Fig. 23—Approximate change in mean temperature at exterior of ingot

there was no further change in the values found for D. In most cases the graph of skin thickness/time did not alter appreciably after the 5th approximation. A typical series of approximations for the 107-cm. level are shown in Fig. 21. Results for the 46-cm. level up to the 16th minute are shown in Fig. 22.

The calculated values of skin thickness are in approximate agreement with the results of experiments by Spretnak,[6] and Nelson,[7] in which the liquid metal was poured out of the solid shell shortly after teeming. These investigators showed that the relation between time and skin thickness could be expressed by the formula $D = K\sqrt{t}$, where D represented the skin thickness, t the time from teeming, and K was a constant.

Attempts have been made by Field[8] and others, to derive this law from fundamental principles of heat flow, although a function of the form $D = K\sqrt{t}$ entailed the assumption of a semi-infinite mould. Since the rate of abstraction of heat depends on the changing conditions of the boundary of the ingot and mould, it is not possible to derive any simple expression relating skin thickness with time.

Separation of Ingot and Mould

Knowing the skin thickness and the rate of heat transfer at the interior and exterior surfaces, it was possible to determine the approximate temperature of the exterior of the ingot.

Again assuming that the change in temperature gradient is constant through the skin, the temperature of the ingot exterior θ_s is given by the approximate expression :

$$\theta_s = z - \frac{D(\delta H + \lambda G \delta D)}{2c}$$

or with the numerical constants included :

$$\theta_s = 1520 - \frac{D}{7{\cdot}2}(\delta H + 412\delta D)$$

The estimated temperature drop between the ingot and the mould is shown for the 107-cm. level in Fig. 23. The temperature of the newly solidified skin fell very rapidly during the first three minutes and then rose slowly at the exterior, while continuing to fall near the solidifying surface.

The rapid fall in the rate of heat transfer to the mould (Fig. 19), and the increase in the exterior temperature of the ingot skin, can only be explained by the separation of the ingot from the mould. It was noticed that the ingots could slip during stripping until they projected about 15 cm. from the narrow end, and as the moulds are tapered 0·027 cm./cm. the gap between ingot and mould at stripping must have been about 0·4 cm.

The formation of the gap might be caused by expansion of the mould, contraction of the ingot, or by both these factors.

As is shown in Fig. 23, which also shows the approximate change in mean temperature of the skin with time, the formation of the gap resulted in an increase in the temperature at the exterior of the ingot. Between the 8th and 20th minute the mean temperature of the skin was very nearly constant and the skin could not be contracting. Owing to the increase in the temperature of the ingot skin and the influence of hydrostatic pressure it is more probable that the ingot expanded slowly during the first ten minutes.

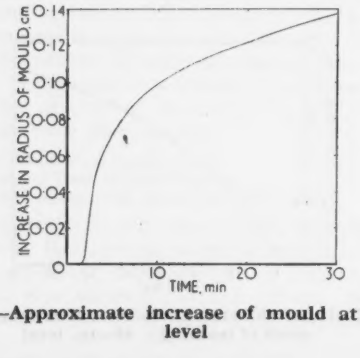


Fig. 24—Approximate increase of mould at 107-cm. level

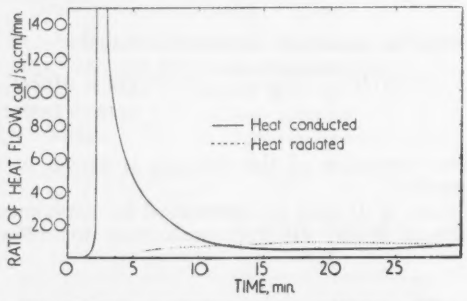


Fig. 25—Relative contribution of radiation and conduction to rate of heat transfer : 107-cm. level

The increase in the internal radius of the mould at the 107-cm. level, calculated on the assumption that Young's modulus is independent of temperature and stress and therefore that the expansion is proportional to the mean temperature,[9] is shown in Fig. 24. This expansion of the mould could therefore be responsible for the formation of a gap shortly after teeming. The effect of longitudinal expansion will be at a minimum at the bottom of the mould and will tend to prolong contact at the top.

Mechanism of Heat Transfer

As the ingot did not fuse to the mould wall there could not have been true metallic contact between them. Heat must have been transferred across the boundary by a combination of conduction, convection, and radiation. There was no rapid gas flow between the ingot and the mould so that the contribution of convection was probably negligible. Heat transfer by radiation between two parallel surfaces is independent of the distance between them and depends only on the temperatures and emissivity of the two surfaces. The rate of transfer by radiation (δH_R) is given by :

$$\delta H_R = \frac{e_1 e_2 \sigma}{1 - (1 - e_1)(1 - e_2)} [(\theta_s + 273)^4 - (\theta_m + 273)^4]$$

Assuming the emissivity of the ingot and mould surfaces to be about 0·5, the contributions of radiation and conduction to the heat transfer at the 107-cm. level would be as shown in Fig. 25. The quantity of heat transferred by conduction depends on the temperature differential between ingot and mould and the effective resistance of the boundary layer. As the mould separates from the ingot skin the rate of heat transfer by conduction decreases very rapidly, and the greater part of the heat is transferred by radiation. Thus the rate of solidification is largely independent of the extent of separation of the ingot and the mould, and even of the mould temperature.

MECHANISM OF INGOT SOLIDIFICATION

From the foregoing results it is possible to outline the process of solidification of a top-run inverted ingot. Where there is no superheat on the metal entering the mould, heat is transferred rapidly from the surface

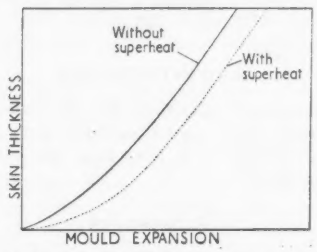


Fig. 26—Relation of skin thickness to mould expansion

of the steel, so that a skin of columnar crystals forms. The faster the rate of cooling the greater the number of nuclei formed, and therefore the smaller the primary crystals. The thickness of the skin at any time must bear a definite relationship to the expansion of the mould wall, as shown in Fig. 26, since both are related to the quantity of heat transferred from the steel to the mould. Owing to the pressure of the liquid steel the skin will be held against the rough mould wall as it expands, so that the skin will be stretched. This will give rise to tensional stresses in the plane of the skin, which, although partially relieved by creep, will tend to pull the skin away from the mould wall, and produce a gap. As the gap between the ingot and mould widens the rate of heat transfer decreases rapidly and the mode of crystallization alters from columnar to random equiaxed. The skin will be thicker at the bottom of the ingot than at the top because of the longer time for which the steel has been in contact with the mould, but gap formation will occur earlier at the top as a result of the lower hydrostatic pressure.

If the steel is above its melting point when teemed, the superheat is transferred to the mould while the skin is very thin and the columnar arrangement of the dendrites is disturbed. The skin thickness corresponding to a given expansion of the mould is less the greater the degree of superheat (Fig. 26). As the skin is thinner, separation of the ingot and mould will be delayed and will occur after a greater expansion of the mould.

MECHANISM OF INGOT CRACKING

It is clearly possible for elastic stresses in the thin skin to increase sufficiently to overcome the weak cohesion between the dendritic crystals so that small cracks are formed. Careful examination of cold ingots, or observation during rolling, shows that large numbers of small irregular cracks with random orientation are present on certain ingots. Large cracks obvious before rolling are invariably transverse, and have evidently developed from favourably orientated minor cracks due to the ingot ' hanging ' in the mould.

This hypothesis accounts for the effect of many factors which can be shown to influence cracking. Sulphur and phosphorus segregated between the dendrites will reduce the rupture strength of the skin. Elements such as chromium, which may be expected to increase the creep strength of austenite, increase the susceptibility to cracking.

Teeming with a high superheat increases the mould expansion corresponding to a given skin thickness, and, by delaying separation, will increase the maximum tensile stress developed in the skin. Teeming at a low rate reduces the mean temperature of the metal in the mould, and will therefore have a similar effect to a reduction in the degree of superheat. ' Off-centre ' teeming results in the major portion of the superheat being removed at one side of the mould, with a consequent reduction in skin thickness at this part.

The location of cracks is determined by points of weakness in the skin such as planes where groups of dendrites of different orientation meet (Fig. 9), or near pockets of gas either within the skin or between the ingot and the mould surfaces (Fig. 10).

Increasing the thickness of the mould walls might be expected to decrease the incidence of cracking, since the thicker walls would expand more slowly giving time for creep to decrease the stresses in the ingot skin. It would be very difficult to predict the effect of other modifications in mould design.

The well-known benefit to be obtained from ' bottom running ' must be caused by the slower rate at which the mould can be filled and by the fact that the reversal of the direction of the convection currents results in more of the superheat being dissipated at the upper portion of the mould. The skin at the lower portion of the ingot will thus increase in thickness more rapidly, so that it is better able to support the pressure of the liquid steel.

APPENDIX

Mathematical Expression of the Relationship between the Thickness of the Solid Ingot Skin, the Quantity of Heat Transferred to the Mould, and the Rate of Heat Transfer to the Mould at Time t

To simplify the mathematical solution the following assumptions are made :

(i) The calculation is carried out for unit area of surface of an infinitely long cylindrical mould
(ii) Liquid metal enters the cylinder instantaneously, and it is not superheated
(iii) The metal freezes at constant temperature (*i.e.*, there is no range of temperature between liquidus and solidus)
(iv) The specific heat, thermal conductivity, and density are independent of temperature
(v) The first derivative of the temperature gradient through the solid ingot skin is constant.

These conditions are fulfilled, for mild steel teemed at a low temperature, with sufficient accuracy to justify the application of the formula to experimental results for heat transfer at the middle of a 3-ton duodecagonal mould.

The symbols are as shown on page 24.

Between the beginning of solidification and time t, D cm. of ingot skin have (1) solidified, giving off A calories, and (2) cooled from the freezing temperature, giving off B calories.

Therefore, the total heat transferred from the skin at time t is :

$$H = A + B \qquad \ldots\ldots(1)$$

Calculation of Latent Heat A—Volume, in cubic centimetres, of element of skin (Fig. 17) of thickness D is :

$$\frac{(2R - D)D}{2R}$$

and

$$A = \frac{\lambda G(2R - D)D}{2R}$$

Calculation of Heat from Solid Skin B—Considering an element dV of the skin of thickness dx at a distance x from the boundary between liquid and skin (Fig. 17) :

$$dV = \frac{R - D + x}{R}\,dx$$

If that element has cooled $T°$ C. from the freezing temperature, the quantity of heat lost from it (dB) is given by :

$$dB = KGT\,dV \qquad \ldots\ldots(2)$$

However, at the boundary between the liquid and solid ($x = 0$) the temperature gradient is related to the rate of increase in skin thickness by the expression :

$$\frac{dT}{dx} = \frac{G\lambda\,\delta D}{c} \text{ and } T = 0$$

At the ingot exterior ($x = D$) the gradient is related to the rate of heat transfer to the mould by the expression :

$$\frac{dT}{dx} = \frac{\delta H}{c}$$

Assuming that $\frac{dT}{dx}$ is a linear function of x (*i.e.*, $\frac{d^2T}{dx^2}$ is a constant) then :

$$\frac{dT}{dx} = \frac{\delta H - G\lambda\,\delta D}{cD}\,x + \frac{G\lambda\,\delta D}{c} \qquad \ldots\ldots(3)$$

Integrating :

$$T = \frac{\delta H - G\lambda\,\delta D}{2cD}\,x^2 + \frac{G\lambda\,\delta D}{c}\,x \qquad \ldots\ldots(4)$$

Thus, substituting for T in equation (2) :

$$dB = KG\left(\frac{\delta H - G\lambda\,\delta D}{2cD}\,x^2 \times \frac{G\lambda\,\delta D}{c}x\right)\frac{R - D + x}{R}\,dx$$

and :

$$B = \frac{KG}{cR}\int_0^D \left(\frac{\delta H - G\lambda\,\delta D}{2D}\,x^2 + G\lambda\,\delta D\,x\right)(R - D + x)dx$$

After integrating, this simplifies to :

$$B = \frac{KG\lambda D^2}{24Rc}\left[(8R - 3D)G\,\delta D + \frac{(4R - D)\delta H}{\lambda}\right]$$

Therefore, from equation (1) :

$$H = \frac{KG\lambda D^2}{24R}\left[\frac{12(2R - D)}{KD} + \frac{G(8R - 3D)\delta D}{c} + \frac{(4R - D)\delta H}{c}\right]$$

Calculation of Temperature of Ingot Exterior—From equation (4) if $x = D$, then :

$$T = \frac{(G\lambda\,\delta D + \delta H)D}{2c}$$

and

$$\theta_s = z - \frac{(GD + H)D}{2c}$$

Calculation of Mean Skin Temperature—The mean value of T is :

$$T = \int_0^D \frac{T\,dx}{D} = \frac{(2G\lambda\,\delta D + \delta H)D}{6c}$$

and the mean temperature of the skin is :

$$z - \frac{(2G\lambda\,\delta D + \delta H)D}{6c}$$

Acknowledgments

The authors wish to thank Mr. T. Urie, B.Sc., for assisting with the experimental work, and the Directors of Messrs. Colvilles, Ltd. for permission to publish this paper.

References

1. D. Binnie : *Journal of The Iron and Steel Institute*, 1944, No. I, p. 353P.
2. V. M. Tageev and B. B. Gulyaev : *Metallurg*, 1939, vol. 14, No. 8, p. 23. Brutcher's Translation No. 1755.
3. B. Matuschka : *Archiv für das Eisenhüttenwesen* 1929, vol. 2, Jan.. p. 405, *Iron and Steel Institute Translation No.* 359, Nov. 1948.
4. Fourth Report on the Heterogeneity of Steel Ingots, *Iron and Steel Institute*, 1932, *Special Report No.* 2, p. 126 and Eighth Report on the Heterogeneity of Steel Ingots, *Iron and Steel Institute*, 1939, *Special Report No.* 25, p. 278.
5. R. Jackson and others : *Journal of The Iron and Steel Institute*, 1944, No. II, p. 211P.
6. J. W. Spretnak : *Transactions of the American Society for Metals*, 1947, vol. 39, p. 569.
7. L. H. Nelson : *Transactions of the American Society for Metals*, 1934, vol. 22, p. 193.
8. A. L. Field : *Transactions of the American Society for Metals*, 1927, vol. 11, p. 264.
9. A. McCance : *Journal of the West of Scotland Iron and Steel Institute*, 1930, vol. 37, p. 101.

The Production of Steel Plates in Scotland

By J. A. Kilby

SYNOPSIS

This paper deals, from historical and technical viewpoints, with the manufacture of steel plates in Scotland, with particular reference to engineering aspects of the subject. The more important developments in works in this area have been considered, and descriptions of plants where steel plates have been made are included; statistical information is also given.

Present-day production methods will form the subject of a later paper.

Introduction

THE production of plates has long formed the most important branch of activity of the Scottish steel industry. A great amount of pioneer work, in both the manufacture and use of plates, was carried out, and many important developments had their origin in the works in this area. This paper reviews the progress that has been made since the first plates were rolled in Scotland, over 70 years ago.

It has been necessary to make extensive research into the past, to verify points of historical significance. Documentary proof has often been difficult, and sometimes impossible, to obtain, and in these cases personal contact has been made with individuals associated with the works concerned. It is important that such information should be recorded, and for this reason a large amount of historical and statistical data is included. At the same time, a strong plea is made for the preservation of drawings and other documents, even where these refer to items of plant or works which no longer exist, as in the past many valuable records have unthinkingly been destroyed.

The Scottish steel industry produces flat-rolled material of all kinds, with the exception of wide and medium strip. The entire range is covered, from sheet to armour plate, but it has been thought advisable to limit the paper to the consideration of plates greater than $\frac{1}{8}$ in. (or 3 mm.) thick.

HISTORICAL[1, 2]

In dealing with the manufacture of steel plates, it is desirable to trace first the development of the steel industry in Scotland.

All the main producing units are located within twenty miles of Glasgow, and owe their origin, primarily, to an abundant supply of easily won coal. Their development was assisted by a well-organized system of railroads and the proximity of port facilities; these conditions also favoured the growth of shipbuilding, structural and heavy engineering industries, which were dependent for their existence on the supply first of iron and then of steel, in sufficient quantities at economical prices.

With the exception of the crucible process, which was of some importance in the early part of the nineteenth century, the first trials with the newer steel processes were initiated in Scotland in 1857. They were carried out at the Coats Iron Works and the Govan Iron Works, using small Bessemer converters, but do not appear to have met with much success. In 1861 a plant consisting of two converters, each of three tons capacity, was installed by Rowan and Co., of Glasgow. From a financial standpoint this plant did not fulfil expectations, and although steel of good quality was produced it ceased operations and was dismantled in 1875.

The Scottish steel industry as it exists today was founded in 1871, when The Steel Company of Scotland, Ltd., was formed, but it was not until 1873 that the first open-hearth steel was made at their Hallside Works. The open-hearth process was then still in its infancy, and the only sizeable works operating in Britain were at Landore, in South Wales. James Riley, the manager of Landore, was appointed to Hallside in 1878, and its success and that of the Blochairn Works of the same Company was largely due to his efforts. The use of open-hearth steel was scarcely past the experimental stage, and many problems had to be solved before it could be manufactured or applied with confidence on a large scale. The steelmakers of the West of Scotland played a big part in this development, particularly where steel for shipbuilding purposes was concerned.

After the initial difficulties had been overcome the rise of the steel industry in Scotland was extremely rapid. In 1885 the basic Bessemer process was introduced at the Glengarnock Works, and in the following year at the Wishaw Works. The first of these plants operated until 1919, and the second, after a short period, was changed to the acid system of working, because of the unsuitability of the available raw materials.

All open-hearth steel was made on the acid hearth until 1890, when the first basic furnace was started. The adoption of the basic process was slow, and it was the conditions brought about by the First World War which accelerated its development. By 1921 the production of basic steel had exceeded that of acid steel for the first time, and in 1949 the former was about ten times the latter.

In Scotland hot metal has never been used on a large scale in the open-hearth furnace, and today, as in the past, the bulk of steel is made by the cold

Manuscript received 11th July, 1950.

Mr. Kilby is at Messrs. Colvilles, Ltd., Motherwell.

pig-iron/scrap process. However, present-day conditions are expected to result in a wider application of the hot-metal system of steelmaking.

At first the energies of the steelmakers were devoted mainly to the production of rails, but as the demand for these became insufficient to keep the mills fully employed, and prices were unremunerative, it was necessary to find other outlets for the steel which the melting shops could produce. The manufacture of plates was therefore introduced, and the first mill for this product was installed at the Hallside Works in 1877.

As was to be expected, the production methods which had been used in the existing ironworks were adapted for steel, this condition being fostered because many ironmakers took up its manufacture. It soon became apparent, however, that heavy equipment of a specialized nature was necessary to deal with the steel in the quantities required, and new plant for heating, rolling and finishing was developed.

Except for the intense activity which characterized the period 1880–1890, progress in methods and machinery has been gradual rather than spectacular. Nevertheless many developments, some of considerable importance, have taken place, and particular attention is drawn to the following items (*see also* Appendix) :

Hallside Works

1878—Reversing combination section and plate mill

Blochairn Works

1884—Reversing slabbing mill
1884—Hydraulic slab shear with steam-pump drive
1890—Reversing universal slabbing mill

Dalzell Works

1894—Reversing slabbing mill with side carriages
1901—Mechanical shearing table

Wishaw Works

1906—Tandem plate mill

Mossend Works

1908—Three-high plate mill with gas-engine drive

Calderbank Works

1909—Three-high plate mill with steam-turbine drive

Clydebridge Works

1923—Three-high plate mill with reversing-motor drive
1923—Mechanized shearing line.

During recent years there has not been scope for major changes, and efforts have been concentrated mainly on improving the performance and efficiency of existing plants. The number of units producing plates has fallen considerably, but the tonnage rolled has remained at substantially the same level. The increase in output from the individual mills has been caused by improvements in the layout and construction of the mechanical equipment ; attention to the ancillary processes, *i.e.*, cooling, shearing, and flattening ; and closer control of operations.

The past and present manufacturers of steel plates in Scotland are listed in Table I, and the locations of the works are shown in Fig. 1. A short historical note on each works follows, and leading particulars of the main units of mill plant are contained in Tables VIII–XIII ; descriptions of items of equipment are given in the Appendix.

Table I

MANUFACTURERS OF STEEL PLATES IN SCOTLAND* (EXCLUDING RE-ROLLERS)

Company	Works	Plate Production Started	Remarks
Colvilles, Ltd. (formerly D. Colville and Sons, Ltd.)	Dalzell	1880	
Colvilles, Ltd. (formerly D. Colville and Sons, Ltd.; formerly the Clydebridge Steel Co., Ltd.)	Clydebridge	1887	
The Steel Company of Scotland, Ltd.	Blochairn	1881	Originally produced wrought-iron plates
Wm. Beardmore and Co., Ltd. (formerly W. and I. Beardmore, Ltd.)	Parkhead	1879	Originally produced wrought-iron plates
The Glengarnock Iron and Steel Co., Ltd. (formerly Merry and Cunninghame, Ltd.), now Colvilles, Ltd.	Glengarnock	1885	Plate production ceased about 1900
The Lanarkshire Steel Co., Ltd.	Lanarkshire	1923	Plate production ceased 1946
The Steel Company of Scotland, Ltd.	Hallside	1877	Plate production ceased 1890
Stewarts and Lloyds, Ltd. (formerly A. and J. Stewart and Clydesdale, Ltd.)	Clydesdale	1884	Plate production ceased 1933. Originally produced wrought-iron plates
Wm. Beardmore and Co., Ltd. (formerly the Summerlee and Mossend Iron and Steel Co.)	Mossend	1880	Plate production ceased 1930. Originally produced wrought-iron plates
The Glasgow Iron and Steel Co., Ltd.	Wishaw	1893	Plate production ceased 1924
James Dunlop and Co., Ltd.	Calderbank	About 1890	Plate production ceased 1929. Originally produced wrought-iron plates

* *See* Fig. 1 for location of Works

Fig. 1—Location of plate-producing plants in Scotland

There are 11 works, excluding re-rollers, in which steel plates have been or are being produced ; three of these no longer exist, and four have abandoned plate manufacture. Of the four works still actively engaged in the trade, one rolls armour plates only. The works engaged on rolling commercial plates are all in the Colville Group of Companies, which is the largest producer of plates in the world, with the exception of some American concerns.

DALZELL WORKS[3, 4, 5]

These works, which are situated at Motherwell, were established in 1871 by David Colville and Sons, Ltd. (now Colvilles, Ltd.), for the manufacture of wrought iron.

In 1880 the open-hearth process of steelmaking was introduced, and equipment for the production of steel plates was installed. At first, the ingots were hammer cogged and the resulting slabs were cut to length under the same hammers, but subsequently slab rolling facilities were added.

As the demand for steel increased, more steelmaking and rolling plant was built, and during the period of greatest activity four melting shops, two slabbing mills, three plate mills, two bar mills and three merchant mills were in operation. Rationalization and improvements to plant have resulted in a considerable reduction in the number of units, and at the present time the rolling equipment for plates comprises one slabbing mill and one plate mill ; with the exception of special-purpose mills for the production of armour, these are the most massive units of their kind in Britain. The manufacture of all commercial heavy plates in Scotland is now concentrated in this plant.

In addition to plates, the Dalzell Works also produce forging ingots, blooms, billets, rounds, bars, wire rods, and light sections.

CLYDEBRIDGE WORKS[5, 7]

These works, which are situated at Cambuslang, were established in 1887 by the Clydebridge Steel Co., Ltd. The plant comprised an open-hearth melting shop, a slabbing mill, and two plate mills, to which more steelmaking capacity and another plate mill were added at a later date.

In the years immediately preceding the First World War the depression in the Scottish steel trade resulted in the works being completely closed. They were taken over in 1915 by David Colville and Sons, Ltd. (now Colvilles, Ltd.). The slabbing mill was immediately altered to produce shell bars, and the melting shop was further enlarged.

The increasing plate requirements of shipbuilders focussed attention on the possibility of re-starting the plate mills, and in 1917 a new open-hearth melting shop and a slabbing mill were built to supply the slabs.

With the ending of the war the demand for shell bars ceased, and a Lauth-type 3-high plate mill was installed so that the output from the two melting shops could be fully utilized. This mill went into service in 1923, and all the mill plant in the old part of the works was abandoned, the buildings being adapted to other uses.

In 1931 the adjoining Clyde Iron Works were acquired from James Dunlop and Co., Ltd., and in 1937 the use of hot metal was introduced into the newer of the Clydebridge melting shops.

Today the output of the works is limited to light and medium gauge plates, mainly for the shipbuilding and structural engineering industries, together with a quantity of slabs for external consumption.

BLOCHAIRN WORKS[4, 6, 8–11]

These works, which are situated at Glasgow, were established in the early part of the last century, for the manufacture of wrought iron. Development was rapid and continuous, and ultimately the works became the largest of their kind in Scotland. Unfortunately, expenditure for new equipment was so lavish that the owners, Hannay and Sons, Ltd., became financially embarrassed and the works closed down about 1875. In 1880 they were acquired by The Steel Company of Scotland, Ltd., which substantially remodelled them for the production of open-hearth steel. James Riley was largely responsible for these changes, and many important developments in the making and rolling of steel were carried out during his association with the works.

Originally, the ingots were hammer cogged and the slabs were rolled into plates on the two existing mills, but in 1884 slab rolling facilities were added. The slabbing mill was of the 2-high reversing type, and was the first mill to be erected specifically for the production of slabs. It was superseded in 1890 by a heavier unit of the universal type, which remained in operation until 1944 when it, in turn, was replaced by a modern high-lift mill.

Plate mills of the universal and Lauth 3-high types were placed in service in 1885 and 1888 respectively, but only worked for a short time. From 1895 onwards the plate-rolling equipment consisted of the slabbing mill and two reversing plate mills ; the light mill was superseded in 1923 by a similar but stronger unit, whilst the heavy mill was abandoned in 1944.

Although plates have always been the main product, bars, sheets, and railway tyres were for many years important items of manufacture at these works. During the Second World War, however, the plant was extensively reconstructed to meet the increased demand for plates, and the manufacture of all other products was discontinued. At the present time production is limited to light and medium gauge plates, mainly for the shipbuilding and structural engineering industries.

PARKHEAD WORKS[5, 8, 10, 12–15]

These works, which are situated at Glasgow, were established in 1835 for the manufacture of wrought-iron forgings. The works changed hands a number of times and ultimately came into the possession of the present owners, William Beardmore and Co., Ltd., under whose management rapid development took place.

From early times, plates of wrought iron and (after the introduction of the open-hearth process to the works in 1879) of steel were an important item of manufacture. Armour plates also figured prominently in the Company's list of products, the first plates of iron having been rolled in 1862.

At first the steel plates were produced by the same methods as those already in use for wrought iron, the

slabs being hammer cogged and rolled into plates on existing pull-over and reversing mills. Slab rolling facilities were added, however, in the early eighties, thus ensuring an adequate supply of slabs for the three plate mills.

Shortly before the First World War a single-stand reversing mill, with rolls 49 in. dia. × 15 ft. long, was installed for the rolling of armour plate ; this is one of the few such special-purpose units still operating in Britain.

Owing to rationalization within the industry, the production of plates for commercial purposes ceased in 1930.

GLENGARNOCK WORKS[8, 14]

These works, which are situated at Glengarnock, between Glasgow and Ardrossan, were established in 1843 by Merry and Cunninghame, Ltd., and consisted originally of blast-furnaces, to which equipment for the recovery of the by-products in the waste gases was added at a later date.

The manufacture of steel by the basic Bessemer process commenced in 1885, the initial products of the works being tinplate blooms and plates. At the time the plant was under consideration there was still some doubt as to the wisdom of using rolled slabs for special duty plates ; it was decided, therefore, to hammer cog the slabs for these, and to roll the remainder.

The open-hearth process of steelmaking was introduced in 1892, and the plant was modified in 1906 to suit the hot-metal system of working. The works were taken over in 1916 by David Colville and Sons, Ltd. (now Colvilles, Ltd.), and a new open-hearth melting shop, also suitable for the use of hot metal, was placed in service in 1917. The Bessemer plant ceased operations in 1919, the original open-hearth melting shop in 1923, and the blast-furnaces in 1930. The manufacture of plates was abandoned about 1900, and today the works produce billets, sheet bars, rails, sleepers, and shipbuilding sections.

LANARKSHIRE WORKS[6]

These works, which are situated at Flemington, between Motherwell and Wishaw, were established in 1889 by the Lanarkshire Steel Co., Ltd. They were erected for the production of open-hearth steel in the form of bars and sections, the rolling plant comprising a 27-in. reversing blooming and bar mill, and small section and guide mills.

Subsequently the manufacture of heavy sections was introduced, this development necessitating the installation of much additional mill equipment. The main unit was a reversing blooming and slabbing mill which was intended to supply blooms to the section mills and slabs to heavy plate mills which were to be installed at a later date. It was thought also that armour-plate rolling could be undertaken, but the mill does not appear to have been used for this purpose. Similarly the rolling of plates on an extensive scale did not materialize, although the original 27-in. blooming and bar mill was modified in 1924 and rolled plates until 1946, when it was closed down and demolished.

The main products of the works are medium and heavy sections and joists, forging blooms and slabs for external consumption.

HALLSIDE WORKS[8, 10, 17–19]

The Hallside Works of The Steel Company of Scotland, Ltd., which are situated at Newton, about six miles from Glasgow, were laid down by William Siemens in 1871 and were the first in Scotland to produce open-hearth steel. At first rails were the chief product, but as the demand for these declined, the manufacture of plates was introduced ; the first steel plates in Scotland were rolled at these works in 1877.

The plate rolling plant consisted of two reversing plate mills and a reversing rail and section mill, which was also capable of rolling plates if required ; all slabs were hammer cogged.

The production of plates was carried on until 1890, when this branch of activity was concentrated at the Company's Blochairn Works. The Hallside Works now produce billets, rails, sections, and steel castings.

CLYDESDALE WORKS[20]

These works, which are situated at Mossend, were established in 1872 for the manufacture of wrought iron.

In 1884 steelmaking by the open-hearth process was introduced, but at first the ingots were hammer cogged and the slabs were rolled into plates on an existing pull-over mill. Slab rolling facilities were added in 1894, and two plate mills in 1901 and 1905 respectively ; these, together with the earlier unit, operated until 1922. It was then decided to abandon all the existing finishing mills and to install, in their place, a single-stand reversing universal plate mill. This decision involved considerable reconstruction of much of the works, and the mill started operations in 1925.

Unfortunately, changing conditions resulted in the cessation of plate manufacture in 1933, and all the mill plant was removed from the site. However, the melting shop continued to function, and at the present time the works are being developed for the production of seamless tubes.

The works were acquired by the present owners, Stewarts and Lloyds, Ltd., in 1903.

MOSSEND WORKS[10, 21, 22]

These works, which are situated at Mossend, were established in 1839 for the manufacture of small sizes of merchant iron. Plate-rolling equipment was subsequently installed, and by 1876 there were two reversing plate mills in operation, one of which was capable of rolling plates up to 6 ft. wide.

The open-hearth process of steelmaking was introduced in 1880, and slab rolling facilities were installed in 1889, another plate mill being added shortly afterwards.

Although the works were considerably successful during their earlier years, failure to effect timely replacement of plant resulted in operations becoming unremunerative. In 1905 the works were acquired by William Beardmore and Co., Ltd., and extensive reconstruction of the plant was immediately undertaken. The existing plate mills were abandoned, and in 1908 a Lauth-type 3-high plate mill, together with

a complete range of finishing machinery, was set to work.

During the First World War the mill was modified to roll shell bars, but on the cessation of hostilities it reverted to its former use.

The manufacture of plates ceased in 1930 and the plant was removed from the site shortly afterwards.

WISHAW WORKS[4, 8, 9, 15, 23–26]

These works, which were situated at Wishaw, were established in 1859 and consisted originally of blast-furnace plant only. The basic Bessemer process of steelmaking was introduced in 1885 but was abandoned in 1893 owing to the unsuitability of the available raw materials. Steelmaking by the open-hearth process commenced in 1894, and in the same year the Bessemer plant was changed to the acid system of working. Heavy mill plant, including slab and plate rolling equipment, was installed about the same time as the open-hearth melting shop, and in 1906 a tandem reversing plate mill, of novel design, was added. The latter mill was the forerunner of most modern light and medium plate mills, and enjoyed a considerable measure of success, despite certain operational difficulties.

The production of plates ceased in 1924 and the works were abandoned shortly afterwards.

CALDERBANK WORKS[27]

These works, which were amongst the earliest of their kind in Scotland, were situated at Calderbank, near Airdrie. They were established for the production of tool steels, but commenced the manufacture of wrought iron early in the last century. The open-hearth process of steelmaking was introduced in the eighties, and slab rolling facilities were added about the same time. The plate rolling equipment comprised a pull-over mill and a reversing mill, the former being replaced in 1909 by a Lauth-type 3-high mill.

The manufacture of plates ceased in 1929 and the works were abandoned.

STATISTICAL INFORMATION

The publication of statistics relating to the production of steel plates is of comparatively recent origin. Apart from figures which have appeared in papers read before the various technical bodies, the main sources of information during the early days of the industry were the annual reports of the British Iron Trade Association. Recently, however, particulars concerning output have been collected and made available by the National Federation of Iron and Steel Manufacturers, and latterly by the British Iron and Steel Federation. It is felt that the value of this paper would be enhanced by the inclusion of information of this nature, and production statistics are therefore given in Tables II–VI; these are shown graphically in Figs. 2–5.

Table II

MERCHANT VESSELS OF 100 OR MORE TONS LAUNCHED ANNUALLY IN THE UNITED KINGDOM AND SCOTLAND*
1920–1949 inclusive

Year†	United Kingdom		Scotland	
	No.	Gross Tons	No.	Gross Tons
1920	618	2,055,624	266	762,183
1921	426	1,538,052	150	551,856
1922	235	1,031,081	88	435,203
1923	222	645,651	73	207,496
1924	494	1,439,885	193	591,656
1925	342	1,084,633	146	538,742
1926	197	639,568	98	289,253
1927	371	1,225,873	161	471,717
1928	420	1,445,920	157	631,917
1929	489	1,522,623	174	588,336
1930	481	1,478,563	182	581,686
1931	148	502,487	67	180,301
1932	100	187,794	39	76,919
1933	108	133,115	37	58,324
1934	173	459,877	71	250,172
1935	185	499,011	87	200,704
1936	328	856,257	132	341,929
1937	309	920,822	131	399,759
1938	267	1,030,375	119	480,454
1939	201	629,910	102	301,520
1940	229	842,910	80	319,972
1941	299	1,192,782	107	455,159
1942	332	1,284,050	102	441,251
1943	287	1,146,006	74	387,487
1944	363	932,164	89	349,980
1945	325	898,238	110	350,535
1946	371	1,133,245	130	408,511
1947	393	1,202,024	136	450,635
1948	342	1,176,346	145	430,701
1949	320	1,267,467	140	515,569

* Source: Lloyd's Register of Shipping
† Prior to 1938 the United Kingdom figures include vessels built in Eire

DEVELOPMENT OF PLANT AND PRODUCTION METHODS

The process of plate manufacture can be divided into three stages :

(i) Steel production
(ii) Slab production
(iii) Plate production,

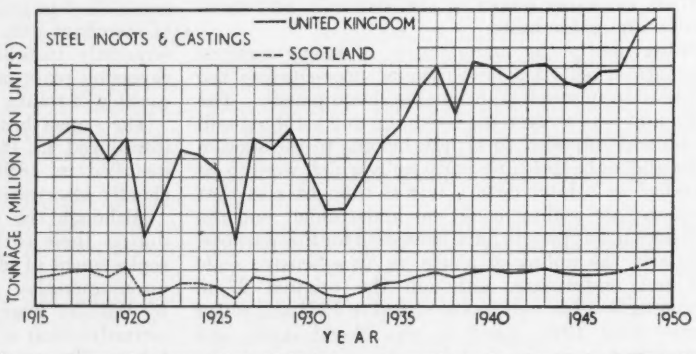


Fig. 2—Annual output of steel ingots and castings in the United Kingdom and Scotland (1915–1949 inclusive)

Table III

PRODUCTION OF STEEL INGOTS AND CASTINGS IN THE UNITED KINGDOM, BY VARIOUS PROCESSES*

1915–1949 inclusive

All values are in thousands of tons

Year	Bessemer		Open-Hearth		Electric		All Other Ingots and Castings	Total Ingots and Castings
	Acid	Basic	Acid	Basic	Ingots	Castings		
1915	821·4	479·8	4090·7	2959·0	20·0	2·0	177·1	8550·0
1916	914·4	542·1	4355·8	2978·9	42·7	4·0	153·8	8991·7
1917	916·3	584·8	4545·2	3355·6	84·6	14·0	216·0	9716·5
1918	754·9	550·5	3880·9	3986·3	78·8	46·6	241·4	9539·4
1919	493·0	296·2	2960·0	3934·8	47·0	30·0	133·0	7894·0
1920	552·5	268·4	3302·1	4682·0	55·2	33·9	173·2	9067·3
1921	184·5	54·0	1136·9	2214·1	10·6	15·9	87·4	3703·4
1922	272·5	196·0	1680·4	3624·3	21·3	18·1	68·0	5880·6
1923	357·8	137·5	2515·7	5278·1	40·9	23·3	128·5	8481·8
1924	405·8	109·7	2358·8	5117·5	41·8	22·7	144·9	8201·2
1925	447·2	27·6	1968·6	4744·0	39·7	24·4	133·9	7385·4
1926	151·7	...	1027·0	2260·4	38·8	22·0	96·2	3596·1
1927	444·1	...	2519·1	5920·9	48·6	25·8	138·6	9097·1
1928	474·4	...	2170·5	5660·8	49·9	28·5	135·6	8519·7
1929	527·1	0·1	2403·8	6480·2	56·6	30·2	138·2	9636·2
1930	255·0	...	1761·0	5091·1	40·4	35·6	142·6	7325·7
1931	112·8	...	1155·1	3777·4	27·8	25·5	104·0	5202·6
1932	111·5	...	1096·7	3905·2	32·2	23·0	92·8	5261·4
1933	189·3	...	1523·7	5132·2	51·4	23·5	103·9	7024·0
1934	222·8	...	1708·4	6667·1	65·6	30·8	155·0	8849·7
1935	199·2	223·8	1812·0	7346·5	77·4	29·4	170·4	9858·7
1936	238·6	323·6	2111·8	8760·6	108·1	44·5	197·4	11,748·6
1937	254·6	417·6	2215·0	9660·0	154·6	60·8	221·4	12,984·0
1938	163·9	430·6	1665·0	7730·9	159·5	63·2	184·8	10,397·9
1939	232·8	701·6	2096·1	9693·1	212·4	79·6	205·7	13,221·3
1940	175·6	738·0	2099·3	9262·0	309·3	126·1	265·0	12,975·3
1941	97·9	695·8	1740·7	8933·7	411·5	161·3	271·3	12,312·2
1942	95·5	726·4	1532·3	9376·9	638·7	221·0	350·9	12,941·7
1943	72·1	731·3	1343·2	9542·1	726·4	265·6	350·5	13,031·2
1944	85·4	708·5	1115·4	9084·5	546·7	248·4	353·3	12,142·2
1945	170·7	687·0	1111·9	9014·0	361·4	180·6	298·8	11,824·4
1946	209·8	723·8	1185·7	9890·0	345·0	134·3	206·7	12,695·3
1947	207·9	678·2	1183·0	9860·7	425·7	150·0	219·0	12,724·5
1948	218·3	786·2	1349·4	11,579·8	526·0	180·8	236·1	14,876·6
1949	226·4	818·8	1314·6	12,220·8	543·6	196·1	232·6	15,552·9

* Source: British Iron and Steel Federation

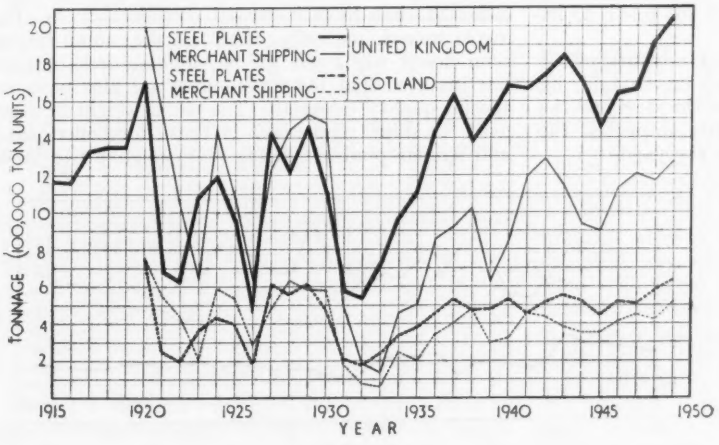


Fig. 3—Annual output of steel plates and merchant shipping in the United Kingdom and Scotland (1915–1949 inclusive)

and it is proposed to consider the subject under these headings. The intermediate stage—slab production—may be omitted, however, as it is in some Continental works, where a slab ingot of a size and weight to suit the individual plate is cast, reheated and rolled directly into the plate. This system was operated experimentally by Riley and others in Britain, but was discarded without ever having been fully established. Although it obviated the need for much heavy and expensive mill machinery, and resulted in savings in power, it complicated the working of the melting shop as a special ingot had to be made for each plate. This meant holding a large stock of ingot moulds and

Table IV

PRODUCTION OF STEEL INGOTS AND CASTINGS IN SCOTLAND, BY VARIOUS PROCESSES* 1915–1949 inclusive

All values are in thousands of tons

Year	Open-Hearth		Electric		All Other Ingots and Castings	Total Ingots and Castings
	Acid	Basic	Ingots	Castings		
1915						1516·2
1916						1671·6
1917	Details not available					1875·0
1918						1923·5
1919						1597·2
1920	1259·8	769·1	0·4	5·0	40·1	2074·4
1921	247·9	318·5	...	1·2	15·8	583·4
1922	265·5	489·9	0·1	0·4	12·2	768·1
1923	504·9	722·2	0·1	2·4	23·3	1252·9
1924	498·1	718·6	...	1·4	23·3	1241·4
1925	406·6	645·6	...	2·8	19·6	1074·6
1926	154·2	253·9	...	2·1	13·5	423·7
1927	631·3	929·7	...	3·3	23·2	1587·5
1928	519·4	879·3	...	3·9	22·5	1425·1
1929	636·8	917·8	...	4·2	22·8	1581·6
1930	448·8	728·1	...	7·7	28·3	1212·9
1931	188·4	465·5	0·2	5·3	16·8	676·2
1932	126·7	404·7	0·7	4·3	16·3	552·7
1933	176·7	596·7	1·2	6·1	18·6	799·3
1934	278·9	900·6	1·5	8·0	31·3	1220·3
1935	338·0	948·3	1·2	8·9	32·9	1329·3
1936	455·8	1132·9	1·3	10·6	36·2	1636·8
1937	440·1	1391·3	1·4	14·7	47·6	1895·1
1938	399·6	1144·8	1·3	14·8	40·9	1601·4
1939	454·3	1377·9	5·6	16·1	21·5	1875·4
1940	491·6	1451·0	25·8	23·9	28·1	2020·4
1941	397·0	1358·8	37·2	25·4	29·7	1848·1
1942	319·7	1402·0	85·1	48·9	33·5	1889·2
1943	283·7	1519·8	119·3	62·2	46·4	2031·4
1944	230·2	1470·7	78·9	44·7	39·9	1864·4
1945	235·2	1432·4	10·6	34·5	34·5	1747·2
1946	261·3	1444·1	9·0	19·3	30·8	1764·5
1947	240·8	1515·5	45·3	20·5	56·8	1878·9
1948	220·2	1871·3	77·6	22·5	62·3	2253·9
1949	208·8	2020·1	65·2	24·1	63·6	2381·8

* Source: British Iron and Steel Federation

scheduling the work of the melting shop with great care, to avoid confusion at the mills. In addition, the yield of saleable material and the surface quality of the finished plates often left much to be desired.

The alternative method has many advantages : it limits the number of different-sized ingots, and, by the increased mechanical working of the steel and the intermediate reheating of the slab, improves the surface finish of the plate, and also the yield.

STEEL PRODUCTION

It is not intended to deal with steelmaking practice as applied to plate manufacture, as this paper is concerned mainly with mechanical aspects of the subject ; nevertheless, some reference to types and sizes of ingot is desirable.

As mentioned previously, the acid open-hearth process predominated until 1921 ; since then basic steel has gained steadily in importance, and the amount of acid steel used for plates is now comparatively small.

There has been little change in the type of ingot, although sizes have increased considerably.[28] The ingot mould normally used is the small-end-up semi-closed top type, of rectangular cross-section, but inverted and hot-top moulds are also used for special quality material. The usual weight of ingot used for ships' plates is 7–11 tons ; for boiler plates and similar products ingots may weigh up to 25 or

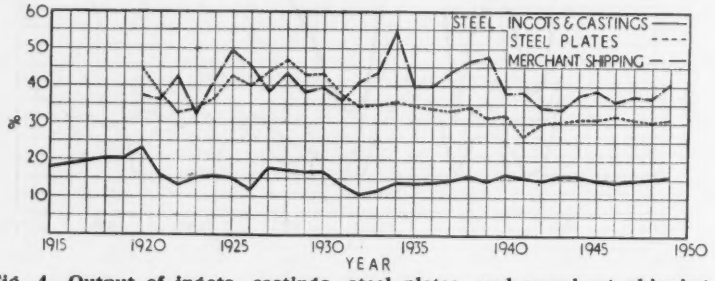


Fig. 4—Output of ingots, castings, steel plates, and merchant shipping, in Scotland, as percentage of total production in United Kingdom (1920–1949 inclusive)

Table V

ANNUAL OUTPUT OF STEEL PLATES IN THE UNITED KINGDOM* 1915–1949 inclusive

All values are in thousands of tons

Year	Plates, Boiler Quality	Plates, ⅜ in. thick or more	Total
1915	No details available		1160·3
1916			1153·4
1917			1326·6
1918			1348·8
1919	178·3	1170·5	1348·8
1920	225·9	1465·3	1691·2
1921	76·7	599·7	676·4
1922	70·3	544·6	614·9
1923	108·8	967·6	1076·4
1924	100·2	1086·0	1186·2
1925	75·6	869·5	945·1
1926	33·0	432·7	465·7
1927	107·1	1303·7	1410·8
1928	79·2	1124·3	1203·5
1929	81·0	1360·0	1441·0
1930	59·0	1040·8	1099·8
1931	36·7	531·3	568·0
1932	45·9	478·1	524·0
1933	65·9	638·2	704·1
1934	86·5	867·6	954·1
1935	91·3	1010·0	1101·3
1936	Not available		1431·2

Year	Plates, Boiler Quality	Heavy Plates, ⅜ in. thick or more	Medium Plates and Sheets, 3 mm. up to ⅜ in.	Armour and Bullet-Proof Plate†	Total
1937	1471·1		152·6		1623·7
1938	1266·2		106·0		1372·2
1939	1294·0		136·4	70·7	1501·1
1940	78·2	1343·2	191·2	63·8	1676·4
1941	78·7	1318·2	185·2	79·7	1661·8
1942	71·3	1328·6	189·4	145·2	1734·5
1943	71·5	1458·5	193·4	112·9	1836·3
1944	67·2	1361·4	173·6	98·5	1700·7
1945	62·0	1196·7	134·8	55·7	1449·2
1946	82·6	1397·4	139·8	13·4	1633·2
1st half 1947	42·5	678·1	72·8	0·9	794·3

Year	Heavy Plates, ½ in. thick or more	Medium Plates, ¼ in. up to ½ in.	Armour and Bullet-Proof Plate	Total
2nd half 1947	566·9	291·6	0·8	859·3
1948	1218·1	685·9	2·4	1906·4
1949	1339·7	697·5	1·5	2038·7

* Source: British Iron and Steel Federation
† Armour and bullet-proof plate previous to 1939 included with "Plates ¼ in. thick or more" and "Heavy Plates"

Table VI

ANNUAL OUTPUT OF STEEL PLATES IN SCOTLAND* 1920–1949 inclusive

All values are in thousands of tons

Year	Plates, Boiler Quality	Plates, ⅜ in. thick or more	Total
1920	138·6	614·5	753·1
1921	38·9	215·9	254·8
1922	36·0	162·6	198·6
1923	63·9	296·4	360·3
1924	76·5	356·1	432·6
1925	48·3	352·5	400·8
1926	20·1	165·4	185·5
1927	77·6	534·5	612·1
1928	64·3	497·5	561·8
1929	62·9	551·4	614·3
1930	43·6	429·3	472·9
1931	22·3	191·4	213·7
1932	21·3	158·8	180·1
1933	29·5	214·6	244·1
1934	44·8	293·8	338·6
1935	54·4	327·3	381·7
1936	Not available		

Year	Plates, Boiler Quality	Heavy Plates, ⅜ in. thick or more	Medium Plates and Sheets, 3 mm. up to ⅜ in.	Armour and Bullet-Proof Plate†	Total
1937	496·6		39·1		535·7
1938	442·9		25·8		468·7
1939	448·6‡		29·4	¶	478·0
1940	57·2§	435·6	43·8	¶	536·6
1941	49·5	358·6	33·9	¶	442·0
1942	43·5	374·4	32·7	64·8	515·4
1943	45·0	420·5	36·1	53·3	554·9
1944	41·1	410·9	37·7	37·4	527·1
1945	39·0	358·1	27·3	24·3	448·7
1946	49·0	429·0	40·0	2·4	520·4
1st half 1947	24·1	204·1	17·8	0·1	246·1

Year	Heavy Plates, ½ in. thick or more	Medium Plates, ¼ in. up to ½ in.	Armour and Bullet-Proof Plate	Total
2nd half 1947	202·8	61·8	0·5	265·2
1948	429·9	151·4	1·0	582·3
1949	482·3	150·2	0·6	633·1

* Source: British Iron and Steel Federation
† Armour and bullet-proof plate previous to 1939 included with "Plates ¼ in. thick or more" and "Heavy Plates"
‡ Estimated on 8 months' actual returns
§ Estimated on 9 months' actual returns
¶ Figures not available

30 tons, whilst for armour plates the ingot may be even heavier.

SLAB PRODUCTION

The first methods employed in the production of steel slabs for subsequent rolling into plates were those already practised in the wrought-iron industry. The slabs were forged from ingots and cut to size under steam hammers of 6–12 tons capacity, after being brought to working temperature in hearth-type reheating furnaces. The slabs made in this manner were well suited to plate manufacture, but as the demand increased during the eighties, alternative methods of production were sought.

Roll cogging or slabbing had already been used to a limited extent, but it was not until 1884 that the first mill specially designed for this duty was installed at the Blochairn Works.[11] It was a reversing mill with 32-in. dia. rolls, and its introduction marked the commencement of a new era in plate production technique.

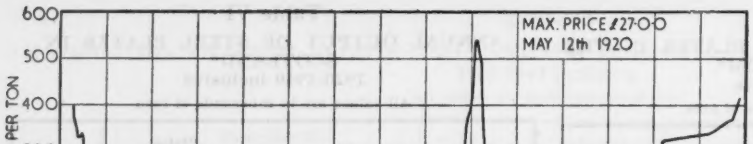


Fig. 5—Selling price of ships' plates (delivered Clyde)

There still existed considerable differences of opinion on the relative merits of the two systems of slab manufacture, and their effect upon plate quality, but investigations eventually showed that equally satisfactory results could be obtained with either method.

The Blochairn mill was followed by many other similar installations, which differed little from the original mill in their essential features. The one noteworthy exception was the reversing universal mill which was installed in 1890, also at the Blochairn Works ; it is the only mill of its type built in Britain for slab rolling duty.

Leading particulars of the slabbing mills in Scotland are given in Table VIII.

Ingot Heating

The earliest furnaces provided for ingot heating were of the Siemens regenerative hearth type, fired with producer gas, although coal-fired units equipped with waste-heat boilers were also used. In 1882 the 'dead' soaking pit was invented by Gjers, and the first installation in Scotland was made at the Blochairn Works in 1884. Other local works followed suit, but the difficulties of maintaining an even flow of ingots from the open-hearth melting shop soon led to the introduction of the 'live' soaking pit or vertical heating furnace.

Considerable thought was given at that time to the question of ingot heating, and its influence on the quality of the finished plate. The results of an extensive study by Riley showed that there was little difference in the properties of plates rolled from slabs which had been made from ingots heated in either unfired soaking pits or vertical heating furnaces.[29]

The modern tendency is to decrease the time required to effect the conversion of the cast ingot to the finished product, but perusal of documents relating to the Blochairn Works shows that even in the eighties of the last century remarkable results were achieved in this direction ; some original notes on this subject are reproduced in Table VII.

The development of ingot heating furnaces has not been characterized by any marked departures from the early designs ; the changes that have been introduced apply mainly to constructional details. Whereas the early pits comprised a number of cells, each accommodating a single ingot and provided with an individual cover which was removed and replaced by the crane or, in later installations, by means of special lid-lifting machines, present-day pits have a single heating chamber with rolling covers, electrically or hydraulically operated. In addition, furnace bindings have been strengthened, high performance refractories and insulating materials applied, and the general standard of the mechanical equipment improved. The advantages to be gained from the judicious use of instruments as an aid to furnace operation have also been appreciated, and they have contributed to the general betterment of ingot heating practice.

Ingot Handling

The relative locations of the steel-melting plant, the ingot heating furnaces, and the slabbing unit are

Table VII

MEMORANDUM FROM BLOCHAIRN WORKS LETTER BOOK ON ROLLING OF PLATES FROM SLAB INGOTS

30.12.1884

Size of slab: 22 in. × 7½ in. × 3 ft. 3 in.
Travelling soaking pit walls: 1 ft. 6 in. thick

27.12.84	1	Cast	12.11 p.m.	Cobbled at 2¼ in. thick
		Stripped	12.17	
		In soaker	12.20	
		Out	12.30½	
		In rolls	12.32	
	2	Cast	1.30 p.m.	Rolled to ½-in. plate
		Stripped	1.39	
		In soaker	1.41	
		Out	1.51	
29.12.84	3	Cast	4.45 p.m.	Rolled to 7/16-in. plate. Rather black when finished
		Stripped	4.57	
		In soaker	5.00	
		Out	5.10	
		In rolls	5.12	
	4	Cast	6.22 p.m.	Cobbled. Bad heat. Too long in soaker
		Stripped	6.28	
		In soaker	6.30	
		Out	6.45	
		In rolls	6.47	
	5	Cast	7.47 p.m.	Rolled to 5/16-in. plate. Finished at a fair red heat
		Stripped	7.53	
		In soaker	7.54½	
		Out	8.01	
		In rolls	8.03	

This ingot was taken from K177. It is interesting to record the time from the pig to the plate:

Previous tap	8.05 p.m.	
Charged	10.20	
Tapped	7.30	
Time in furnace	9 hr. 10 min.	
Between taps		11 hr. 25 min.
At transfer hoist	7.39 p.m.	
In centre ladle	7.41	
Ingot teamed	7.47	
Stripped	7.53	
In soaker	7.54½	
Out	8.01	
In rolls	8.03	
Finished plate	8.09	
From tap to plate		39 min.
Total time:		12 hr. 4 min.

of extreme importance. In the early installations, lack of space and the need to conserve capital resources resulted in the units being laid down in close proximity to one another, thus minimizing the amount of handling, and economizing in fuel. So long as outputs were small and no attempt was made to raise them appreciably beyond the design figures, these layouts were perfectly satisfactory. With increasing demands and the greater capacity potential of the newer plants, however, the individual units tended to become more dispersed, so giving rise to difficulties in the movement of materials and the co-ordination of operations; fortunately, conditions in this respect have been favourable in most Scottish works.

At first the ingots were handled from the casting pit to the heating furnaces and thence to the mill, or hammer, by means of hydraulically operated jib cranes or steam travelling derrick cranes. These were later superseded by steam or electrically driven overhead cranes, the ingot being gripped by simple tong gear suspended from the crane hook. No special stripping equipment was provided, the usual treatment with 'stickers' being to dump the ingot and mould on the floor or to swing them, while suspended from the crane, against a stationary object. Some of the more recent cranes have been fitted with a loose hoist barrel which enables the ingot and mould to be elevated and then to fall by gravity to the ground, thereby imparting a severe blow to the mould and loosening the ingot.

The tong gear originally used was inconvenient, as 'dogging on' had to be manually assisted; to overcome this difficulty the centre-lift self-dogging crane was introduced. This enabled all lifting motions to be controlled by the driver, and entirely dispensed with labour on the floor. More recently, cranes of the rigid mast type have been installed, one of which is capable of dealing with ingots up to 17 tons in weight.

The method of receiving the ingot at the mill has been practically the same in all works. Usually, a hydraulically operated tilting chair is provided at the end of the approach roller table, into which the ingot is placed vertically by the crane, the chair being turned through 90° to lay it on to the rollers. In some cases the ingot is lowered directly on to the table by the crane, but this is not desirable, as damage may be caused to the mill elements through careless handling.

Where the distance between the heating

Table VIII

PARTICULARS OF SLABBING MILLS IN SCOTLAND

Works	Mill			Slab Production		Prime Mover				
	Type	Roll Size		Started	Ceased	Engine				Ratio
		Nominal Dia., in.	Length, ft. in.			Type	Bore, in.	Stroke, in.	Working Pressure, lb./sq. in.	
Blochairn	Duo reversing	32	6 3½	1884	1890	Twin non-reversing	36	48	90	2·75:1
Blochairn	Duo reversing universal	28		1890	1944	Twin reversing	48	54	100	2·66:1
Blochairn	Duo reversing	35	8 6	1944	Operating	Triple reversing	40	54	100	2·5:1
Glengarnock	Duo reversing	36	7 6	1885	About 1900	Twin reversing	42	60	80	
Calderbank	Duo reversing	40	7 6	About 1890	1929	Twin reversing	40	60	80	2·86:1
Wishaw	Duo reversing	40	8 6	1893	1924	Twin reversing	46	60	100	1·75:1
Parkhead	Duo reversing	40	8 6	1888	Operating	Twin reversing	42	60	120	2·5:1
Mossend	Duo reversing	39	8 2	1889	1930	Twin reversing	45	60	100	2·5:1
Lanarkshire	Duo reversing	40	9 6	1898	Operating	Twin reversing	46	60	100	2:1
Clydebridge	Duo reversing	28½		1888	About 1921	Twin reversing	38	60	100	
Clydebridge	Duo reversing	33	7 6	1917	Operating	Twin reversing	48	54	120	2·67:1
Clydesdale	Duo reversing	40	8 6	1894	1933	Twin reversing	42	60	100	2·5:1
Dalzell	Duo reversing	33	8 6	1894	1920	Twin reversing	44	60	100	2·75:1
Dalzell	Duo reversing	36	10 0	1913	Operating	Twin reversing	48	60	100	3:1

Remarks
Engine fitted with mechanical reversing gear
Mill reconstructed in 1915 and roll size altered to 34 in. × 7½ ft.
Working pressure increased to 160 lb./sq. in., and cylinder altered to 38-in. bore in 1938
Mill electrified in 1937. Motor connected through 2:1 reduction gear to bottom pinion. Motor cut-out torque, 180 metre tons; motor speed, 0–45–120 r.p.m.
Mill reconstructed in 1925 and rolls lengthened to 9½ ft.
Mill electrified in 1937. Motor direct-coupled to bottom pinion. Motor cut-out torque, 225 metre tons; motor speed, 0–60–120 r.p.m. New mill train installed in 1945 with rolls altered to 44 in. × 10 ft. Capacity of electric drive increased to 300 metre tons

furnaces and the mill is appreciable, the provision of additional machinery to transfer the ingots may be necessary. It may take the form of a gravity roller table with a hydraulic lifting device for elevating the ingot as in the earlier plants, or a travelling roller table or bogie on which the tilting chair is mounted. Equipment of this type minimizes the use of the heavy cranes, and also ensures greater flexibility of working.

Slabbing Mills

The slabbing mill forms one of the major units of any plate rolling plant and constitutes, in an engineering sense, a most interesting field of study.

Prime Movers—The driving of slabbing mills does not present any serious problems, and the conditions imposed are not difficult to fulfil. The main requirement is that the prime mover should be capable of developing sufficient power to deal with the maximum sized ingot, but as the number of pieces to be handled is relatively small, the speed factor is not of primary importance. Successful operation can be assured by the use of a driving unit of moderate size, geared to give the requisite torque at the rolls.

All slabbing mills in Scotland have been of the 2-high type, necessitating the use of reversing drives. The first mill installed at the Blochairn Works was driven by a twin-cylinder continuously running engine fitted with mechanical reversing equipment and speed-reducing gear, and was similar to the plate-mill drives then in use. This type of engine was not used in later installations, however, and subsequently all slabbing mills were powered with simple non-condensing twin-cylinder horizontal geared reversing engines. According to modern engineering standards these engines were of crude design ; nevertheless they contrived to function under all sorts of conditions, their robust simplicity undoubtedly accounting for the measure of success which they achieved.

The first electric drive for slabbing mill duty was installed at the Dalzell Works in 1932, when the original twin-cylinder steam engine was replaced by a direct-coupled motor. Following this conversion, the drive for the slabbing mill at the Clydebridge Works of the same company was dealt with in a similar manner.

The only other example of a pure slabbing mill still operating is at the Blochairn Works, and is driven by means of a triple-cylinder simple non-condensing reversing engine. This is a rather special case, however, as it was installed under emergency conditions during the Second World War, and incorporated an existing engine unit.

Leading Couplings—The prime mover is coupled to the mill by means of a leading spindle or coupling arranged between the output shaft of the driving unit and the bottom pinion. In the earlier installations a fluted spindle was used, of sufficient length to permit the withdrawal of the coupling boxes when disconnecting the drive from the mill. The spindle also acted as a breaking member to safeguard the mill parts in case of overload, and it ensured a degree of flexibility between the drive and the mill to allow for misalignment caused by uneven wear of bearings and settlement of foundations.

This type of coupling has now been abandoned, as the clearances between the transmission surfaces were considerable and the resulting slogger induced severe shock-loading of the mill parts. At the present time, couplings of the universal slab or Bibby types are used, and these have assisted considerably in the attainment of smooth and trouble-free running.

Pinion Housing Units—The evolution of the pinion housing unit has enabled mills to be operated more efficiently, and has resulted in considerable reductions in power and maintenance charges. In the first mills, cast-steel pinions with moulded straight teeth of coarse pitch were mounted in cast-iron or steel housings. The bearings were flat-backed gunmetal steps with means for adjustment to compensate for wear, but no special provision was made for lubricating either these or the gear teeth, and the mechanical efficiency of the unit was low. Minor changes were introduced in some of the later installations of this type, *i.e.*, staggered straight and double helical teeth, improvements in the design of the bearings, and the enclosure and lubrication of the pinions, but the first pinion housing with totally enclosed and continuously lubricated machine-cut pinions and white-metal-lined bearings was installed at the Clydebridge Works in 1937, with the electrification of the slabbing mill.

Driving Spindles—The pinions of the earlier mills were coupled to the rolls by means of fluted wobbler spindles and coupling boxes, the bottom spindle being supported in a spring-mounted bearing whilst the top spindle, in view of its considerable vertical lift during the edging passes, was counterbalanced by weights or hydraulic power. Often the length of the spindle was insufficient to ensure smooth turning of the roll at high lifts, and the adverse effects of a steep angle of inclination were aggravated by the large but unavoidable clearances between the driving surfaces of the spindle and the coupling boxes. Eventually these weaknesses were recognized, and longer spindles with universal couplings were introduced, as opportunity arose.

Present-day slabbing-mill transmission systems are designed to deliver to the rolls, with the highest possible efficiency, the power developed by the prime mover. The achievement of this aim has resulted in more sustained operation of the mills, owing to the decrease in the number of breakdowns, because the energy previously lost was being expended mainly in wearing out the driving elements.

Roll Stands—The roll stand of the modern slabbing mill differs considerably from its prototype of sixty years ago, although most of the changes have been evolutionary in character.

The first roll housings were of cast iron with vertical posts of rectangular cross-section and flat bases similar to those of the pinion housings. They were held in position by means of wooden and iron wedge-pieces driven into the spaces formed between the inclined vertical faces of the housings and the bedplate, no bolts being required. The bedplates were also of cast iron, and were of sufficient length to accommodate not only the roll housings but also the spindle balance bracket and pinion housing. In more recent installations, however, cast-steel roll housings have been used which sit on the flat-vee facings of cast-steel bedplates,

to which they are secured by bolts and shrink rings.

Considerable attention has been paid to roll-neck mountings, and great progress has been made in their design and application during recent years.[30] The operating conditions are not easy ; although bearing pressures are relatively low, other difficulties (such as the presence of heat and scale) can be very troublesome. Bearing troubles caused by scale, which are more pronounced for the bottom roll, are accentuated because the edging passes are always located adjacent to the bearings, and are only separated from these by relatively narrow collars. These passes have always been regarded as major influences in removing from the faces of the slab the scale which, after being loosened during the flat passes on the barrel of the roll, is shed almost completely in the edging passes. In the older mills little or no attempt was made to protect the necks and bearing surfaces from the ingress of scale, with the result that bearing wear was excessive, and deterioration of the roll necks could not be avoided.

Roll-neck bearings were always of the multi-part type, the bottom roll being mounted in two bearings, each consisting of one bottom step and two side steps, and the top roll having an additional step in each of the carrier chocks, for purposes of support. End adjustment of the rolls was effected by inserting liners behind the steps or by the use of setting pins bearing on the steps or chocks.

The bearings now are generally of the white-metal-lined steel-shell type with forced-feed grease lubrication and direct and indirect water-cooling, special precautions being taken to exclude scale and other foreign matter. The shells are fitted into steel chocks, and provision is made for adjusting these endwise, by means of setting pins or keeper plates which also control the end clearance of the rolls.

Vertical adjustment of the top roll between passes has always been effected by conventional methods. The gear used consists of a vertical screw rotated by a worm wheel and worm from a small steam engine or one or two electric motors, and working in a nut in the top of each roll housing. The first Blochairn Mill differed in that the nuts and not the screws were rotated, but the principle was the same. An important feature of the newer installations is the high speed of screwing which is necessary in slabbing mills, where the edging of wide slabs calls for considerable lift of the top roll.

So that the top roll may follow the screws it must be held in contact with these, through the chocks and breaker blocks, by means of suitable balance gear. This has always been of the direct-acting hydraulic type ; it consists usually of a cylinder mounted directly below each roll housing, exerting pressure upwards through two thrust rods on to each carrier chock. This system is effective, but has the disadvantage that the cylinders are subjected to the influence of scale and water and are very inaccessible. In the latest installation this difficulty is overcome by the use of the overhead type of balance gear, in which the cylinders are mounted on the tops of the roll housings.

Rolls—The rolls of the original Blochairn Mill were of cast iron, but in most subsequent installations they have been of cast or forged steel. More recently, special compositions have been developed which offer greater resistance to the effects of heat and abrasion, but much still remains to be done in this respect.

The roll generally used has a plain central portion of sufficient width to cover the largest ingot or slab to be rolled, and has an edging pass at each end ; the size of the edging pass depends on the method of rolling and whether the mill is called upon to produce bloom sections as well as slabs.

Roller Tables and Manipulators—The movement of the ingot or slab to and from the rolls and its manipulation between passes involve the use of very powerful mechanical equipment. Considerable ingenuity has been exercised in its development and many interesting devices have been evolved.

The transportation of the piece is normally effected by roller tables arranged at each side of the rolls. At first the rollers were driven by means of a small steam engine through spur and bevel gearing, one driving unit serving the rollers on both sides of the mill. The rollers, which were of cast iron mounted on steel shafts, were reduced in diameter at each end to match the passes in the mill rolls, and all gears had cast teeth. No special provision was made for the lubrication of these or of the bearings, and as a result upkeep cost was considerable. On some of the later mills, undriven rollers were used and the piece moved on these in the direction of rolling by long-stroke hydraulic cylinders, but with one exception this system was not persevered with, and the use of ' live,' or driven roller tables became accepted practice. The steam engine was superseded by the electric motor, and the feed rollers were split into two groups, one on the entry side and the other on the delivery side of the rolls.

The first roller, or breast roller, has always been the subject of much serious thought, as it is one of the most heavily loaded items of equipment in the mill. Often this roller is undriven, and rotates loosely in simple gunmetal bearings located in pockets in the roll housings. From time to time efforts have been made to drive the breast roller positively, so as to facilitate the handling of short ingots or slabs to and from the mill rolls. Bevel gears, spur gears, and chains have all been tried with varying success, but the solution to the problem seems to lie in the use of direct-coupled electric motors of special design.

The importance of mechanical aids in manipulating the ingot or slab between passes was soon recognized as fundamental, and every slabbing mill has been equipped with devices for this purpose. Many different types have been used, from the simple hydraulic cylinder mounted below and between the rollers of the feed table, which could engage the piece and turn it on edge, to the modern universal sideguard type of manipulator. In view of the magnitude of the pieces to be handled speed of operation has not been of vital importance, and greatest stress has been laid on the ability of the equipment to deal with maximum loads under all operating conditions.

Slab Cutting

In the manufacture of iron plates the forged slabs were cut to size under the hammer, and it was natural

that the same method should be adopted for steel. With the increasing output of open-hearth steel-melting furnaces, and the contemplated introduction of rolling mills for the production of slabs, it became apparent that some alternative system of cutting-up was necessary.

In the eighties of the last century the largest producer of steel plates in the world was The Steel Company of Scotland, Ltd., which, as befitted its position in the industry, was constantly striving to improve its plant and technique. It is interesting, therefore, to read a report dated 1st October, 1883, concerning improvements at the Blochairn Works. The following is an extract from the report :

" *Cutting Slabs—Hammer versus Guillotine*

After much thinking of ways, means and results, I feel most strongly impelled to ask you to face your original intention of putting down a guillotine to cut 24 in. × 8 in. slabs.

If the hammers are employed, two will be required at least. There will be barely time to cut the ends off the slab. The cutting itself will cost at least 9*d.* per ton on plates. The scrap will be as much lost as it is at present. The same liability to have slabs cut off the square and to wrong weights will exist, and therefore the plate mills will suffer. A large number of men will be required to handle the material. We will be open to annoyance from the very men who will conceive themselves sufferers by the introduction of the cogging process.

By using a guillotine the ends of the slab will be cut perfectly square and the slab itself cut to weight without difficulty. A most important point is that the speed of cutting will permit of the extreme spongy end being sheared off, and then *any extra length may be cut into blooms* for rolling direct into angles, etc., in the 16-in. mill . . . the great saving in labour and the facility with which the slabs can be run on to bogies and locomotived to the mills or central slab crane should be considered.

A guillotine—driven from the rolls if need be, but better by separate engine—solves all difficulties. Without it, our appliances are but half complete."

After considerable study, during which the relative merits of the hydraulic and steam-engine-driven types of shear were closely investigated, the first guillotine was installed at the Blochairn Works in 1884. This shear was of the hydraulic down-cutting type, having a single 36-in. dia. cylinder and capable of exerting a maximum cutting pressure of 1000 tons (which, it was thought, would be required when dealing with slabs 24 in. wide × 8 in. thick) ; hydraulic power at 1 ton/sq. in. was furnished by a steam-driven pumping engine. This shear was replaced in 1890 by a machine of similar design but of larger capacity. It was capable of exerting a maximum pressure of 1450 tons at the blade, and of cutting slabs up to 60 in. wide × 8 in. thick.

No more shears of this type were built, and during the next 20 years or so most new units were of the steam-engine-driven down-cutting type. They were powered by twin-cylinder horizontal or vertical steam engines, coupled to the shear's camshaft through reduction gearing, and were not fitted with flywheels as the engines were capable of exerting sufficient power to effect the maximum cut from rest.

In 1913, a slab shear employing the steam-hydraulic system and having a capacity of 66 in. wide × 18 in. thick was placed in service at the Dalzell Works ; this is still the largest unit of its type in the world. Leading particulars of the slab shears installed in Scotland are given in Table IX.

Slab Shearing—The efficient operation of the slab producing unit depends, to a large extent, on the manner in which the rolled material is handled after leaving the rolls. The shearing plant is therefore of great importance, and to ensure a high standard of performance it must be capable of clean, accurate, and speedy cutting.

The sheared ends must be clean and square to the longitudinal sides of the slab, and for this reason it is important that the blades should be sharp and correctly set in relation to each other. The shear design must permit of the blades being easily changed and must allow proper access to the working parts, so that adjustments can be carried out expeditiously. Also, provision of an efficient holding-down mechanism minimizes the danger of slab movement during cutting.

Slabs for subsequent rolling into plates must be cut accurately to size and weight, otherwise scrap loss will be excessive or undersized plates will result. The

Table IX

PARTICULARS OF SLAB SHEARS IN SCOTLAND

Works	Type	Prime Mover	Size, in. × in.	Remarks
Dalzell	Hydraulic	Steam intensifier	66 × 18	
Clydebridge	Hydraulic	Steam intensifier	40 × 10	
Blochairn	Hydraulic	Steam intensifier	60 × 13	
Lanarkshire	Hydraulic	Steam intensifier	40 × 10	Upcutting type
Blochairn	Hydraulic	Twin pumping engine	24 × 8	Abandoned
Glengarnock	Geared	Twin engine	30 × 9	
Clydebridge	Geared	Twin engine	36 × 10	
Parkhead	Geared	Twin engine	36 × 12½	
Mossend	Geared	Twin engine	38 × 11	
Calderbank	Geared	Twin engine	48 × 12	
Blochairn	Hydraulic	Twin pumping engine	60 × 8	
Wishaw	Geared	Twin engine	42 × 12	
Dalzell	Geared	Twin engine	60 × 12	
Dalzell	Hydraulic	Steam intensifier	36 × 7	
Clydesdale	Geared	Twin engine	40 × 14	
Lanarkshire	Geared	Twin engine	60 × 14	

attainment of the necessary accuracy in cutting depends primarily on the skill of the shears operator, but it can be influenced greatly by the layout and equipment of the plant. The provision of an efficient stop-measuring gear is essential, and the operator must be positioned so that he has a clear vision of the measuring scale, the slab, and the shear blades, at all times. The stop-measuring gear must be of robust construction, and must be arranged so that it can be used as a pusher for exact positioning of the slab when cutting, or to assist in turning short slabs or crop ends so that they can be conveyed more easily by the roller table.

Where slabs of light weight are being produced from relatively large ingots, the number of pieces to be handled at the shear is considerable. To minimize the possibility of delay at the mill under these circumstances, the shear must be speedy in operation; the provision of ample power in the driving unit is therefore essential. The ancillary equipment must also be designed and laid out to deal with the mill product at the maximum rate of cutting

Slab Disposal—The method of disposing of the slabs after shearing is influenced by the method to be used for converting them into plates. There are two possibilities, the cut slabs may be charged to the reheating furnaces while still hot, thus economizing in fuel, or they may be allowed to cool for inspection and surface conditioning. The latter system is employed for special quality plates that require intermediate dressing of the slabs; the only other circumstance in which slabs are allowed to cool is in the event of the plate mill being unable to accept them owing to breakdown of plant or other similar cause.

At first the slabs were removed from the shears delivery table by steam or hydraulically operated jib cranes, which placed the slabs on cars or in iron wagons for delivery to the plate mills. This type of crane was superseded by steam or electric overhead cranes fitted with lifting tongs or cradles, and in plants where the slabbing and plate mills were close together the slabs were transferred direct from the shears table by crane or charging machine. In more recent installations, use is made of roller tables and bogies for transferring the slabs to the plate mill at floor level, thus obviating the need for crane service.

If the slabs are to be allowed to cool they can be removed by crane and stacked on the floor, or they can be

Table X

PARTICULARS OF TWO-STAND REVERSING PLATE MILLS IN SCOTLAND*

Works	Size of Rolls				Plate Production		Prime Mover					Remarks
	Roughing		Finishing				Engine				Ratio	
	Dia., in.	Length, ft.	Dia., in.	Length, ft.	Started	Ceased	Type	Bore, in.	Stroke, in.	Working Pressure, lb./sq. in.		
Hallside	26	7	26	7	1877	1890	Twin reversing	34	48		Direct coupled	
Hallside	26	7	26	7	1878	1890	Twin reversing	34	48		Direct coupled	
Dalzell	28	8	28	8	1880	1921	Twin reversing	40	54	80		Engine also drove 27-in. bar mill
Dalzell	36	14	34	10		Operating	Twin reversing	46	60			Engine rebuilt in 1906 as 37 in. × 55 in. × 60 in. twin tandem compound; mill train reconstructed in 1937 and rolls altered to 44½ in. × 14 ft. and 44½ in. × 9½ ft. Ratio of reduction gear, 2·5:1
Dalzell	28	7	30	6½		1927	Twin tandem compound reversing	37 and 56	54		Direct coupled	
Glengarnock	26	7½	26	7½	1885	About 1900	Twin reversing	42	60	80		Engine also drove 36 in. × 7½ ft. blooming and slabbing mill until 1909, when additional engine of same size was installed for plate mill
Clydebridge	29	8	29	8	1887	1921	Twin reversing	38	60	50		
Mossend	29	8	29	8		1905	Beam reversing			50		
Mossend	26	6½	26	6½		1905	Beam reversing			50		
Calderbank	36	10	36	8½	1890	1929	Twin reversing	48	54	80	2·35:1	Roughing rolls increased to 12 ft. long and later altered back to 10 ft.
Wishaw	30	8	30	8	1893	1924	Twin reversing	52	60	100	2·5:1	Engine also drove 40 in. × 12 ft. single-stand plate mill
Blochairn	28	8	28	8			Twin tandem compound reversing			100		Continuously running engine also drove 28 in. × 19 in. × 8½ ft. three-high mill.
Blochairn	33	10½	28	8		1946	Twin reversing	42	54	100	2·16:1	Rolls increased to 34 in. × 13 ft. and 34 in. × 10 ft.
Blochairn	32	8	32	8	1923	Operating	Triple reversing	46	54	100	Direct coupled	Mill train reconstructed in 1941, and rolls increased to 34 in. × 8 ft.
Clydesdale	28	7½	30	7½	1901	1922	Twin reversing	42	60	100	Direct coupled	
Clydesdale	36	12	35	10½	1905	1922	Twin reversing	52	60	100	1·5:1	
Lanarkshire	27	7	33	7	1924	1944	Twin reversing	45	60	100	Direct coupled	27-in. blooming and bar mill originally installed in 1889

* This Table includes most of the mills of this type, but a few have been omitted because of absence of information

Table XI

PARTICULARS OF THREE-HIGH PLATE MILLS IN SCOTLAND

Works	Size of Rolls				Plate Production		Prime Mover		Mill Speed, r.p.m.	Remarks
	Top and Bottom		Middle		Started	Ceased	Type	Size, h.p.		
	Dia., in.	Length, ft. in.	Dia., in.	Length, ft. in.						
Blochairn	28	8 6	19	8 6	1888	1894	Steam engine		70	Driven by twin compound continuously running engine with flywheel which also drove 28 in. × 8 ft. two-stand plate mill
Mossend	29½	7 8½	21½	7 8½	1908	1930	Gas engine	1850	75	Gas engine replaced in 1918 by electric motor, 2000 h.p., 300/270 r.p.m., coupled to mill through single reduction gear unit
Calderbank	28	7 0	19	7 0	1909	1929	Steam turbine	750	70	
Clydebridge	36	9 0	24	9 0	1923	Operating	Reversing motor	4500	0-65-110	

pushed or drawn from the roller table on to cooling banks or into piling pockets.

Crop End Disposal—The handling of crop ends presents some difficulty, chiefly because of their short length and awkward shape, and although various systems have been evolved for dealing with them, none of these systems fulfils all conditions satisfactorily. In the early plants, the cranes provided for handling the slabs also dealt with crop ends, these being lifted with tongs and placed in iron wagons for return to the melting shop. A later development was the provision behind the shear of a hydraulically operated pusher gear, which removed the crop ends from the roller table into charging boxes or skips arranged alongside ; when filled, these were lifted away by the crane and replaced by empty ones. In spite of many limitations this latter system is still the most widely used for slabbing mill duty.

PLATE PRODUCTION

As for slab production, the methods and equipment first used for converting the slabs into plates were similar to those already employed in the wrought-iron industry ; as demands increased, however, the methods were modified to deal with the greater outputs and larger plates.

The first steel plates were rolled in 1877, on a mill specially built for the purpose. This mill followed closely the design of unit already in existence, being of the 2-stand 2-high reversing type. At an early date the Lauth-type 3-high mill was introduced at the Blochairn Works. This was abandoned after a short period of operation, owing to constructional weaknesses, and all plates rolled in Scotland were produced on reversing mills until 1908, when the first successful 3-high mill was installed at the Mossend Works. In 1925 a single-stand 2-high reversing universal mill was started at the Clydesdale Works : it was not the first mill of its type in Scotland, as a similar unit was in operation at the Blochairn Works as long ago as 1885, rolling narrow plates and strips.

Armour-plate manufacture has been an important branch of activity for many years, and special equipment for dealing with it has been available since the days of iron armour. Whilst almost any kind of plate mill is capable of rolling this material, the mill in general use for its production is of the single-stand 2-high reversing type ; one stand of rolls suffices, as the amount to be rolled is small and consequently the problem of surface finish does not arise. Leading particulars of plate mills in Scotland are given in Tables X–XIII.

Considerable developments have taken place in ancillary equipment and services, and present-day mill performances are only made possible by the facilities now provided for dealing with the plates after they leave the rolls ; in fact, these features usually determine the output of a plant.

Slab Conditioning and Stocking

In contrast to practice in America, where slabs are usually allowed to cool before delivery to the plate mill, Scottish works have always endeavoured to charge them at the maximum temperature, direct into the reheating furnaces. This system, which has been

Table XII

PARTICULARS OF SINGLE-STAND REVERSING PLATE MILLS IN SCOTLAND

Works	Size of Rolls		Plate Production		Prime Mover					Remarks
					Engine				Ratio	
	Nominal Dia., in.	Length, ft.	Started	Ceased	Type	Bore, in.	Stroke, in.	Working Pressure, lb./sq. in.		
Wishaw	40	12	1893	1924	Twin reversing	52	60	100	2:1	Engine also drove 30 in. × 8 ft. two-stand reversing plate mill
Clydebridge	42	13½	About 1912	1914	Twin reversing	38	60	100	Direct coupled	Engine also drove 29 in. × 8 ft. two-stand reversing plate mill
Parkhead	49	15	1913	Operating	Twin reversing	42	60	120	7·38:1	Armour-plate rolling mill

Table XIII

PARTICULARS OF SPECIAL PLATE MILLS IN SCOTLAND

Works	Type	Number of Roll Stands	Size of Rolls		Plate Production		Prime Mover				Remarks
			Nominal Dia., in.	Length, ft.	Started	Ceased	Type	Bore, in.	Stroke, in.	Working Pressure, lb./sq. in.	
Blochairn	Duo reversing universal	One	20	To suit 30 in. max. width	1885	About 1900	Twin reversing engine	36	48	100	
Wishaw	Duo reversing universal	Two	30	6½	1906	1924	Single reversing compound engine	42 and 67	48	160	Speed of finishing rolls 15% higher than roughing rolls
								Size, h.p.	Speed, r.p.m.		
Clydesdale	Duo reversing universal	One	34	8	1925	1933	Electric reversing	4500	0 80 135		

highly developed through the years, results in minimum fuel consumption, reduces the amount of material in circulation, and simplifies managerial functions ; it does not, however, provide any appreciable buffer between the slabbing and plate mills, to cover breakdowns or other interruptions of the flow of slabs. The growing demand for special quality plates, for which the slabs must be conditioned and/or inspected before further processing, increases the volume of cold stock, and facilities for dealing with this must be provided. Previously such material was stocked adjacent to the slabbing mill or reheating furnaces, but separate buildings or extensions to mill or furnace buildings are now used for the purpose ; provision is also made for re-introducing the cold slabs into the process line when required.

Slab conditioning, or the removal of surface defects, is usually carried out by means of oxy-acetylene hand torches. This method is equally effective for most grades of steel, although chipping or grinding may be resorted to in special cases.

Slab Heating

The heating of slabs varies from a wash heat to a full reheat, depending on whether the material is hot- or cold-charged. Since Scottish works have always favoured the hot-slab system, reheating furnaces have been designed primarily as wash-heating units, and as the delivery of slabs from the cogging department is often of an intermittent nature, the furnaces are of the batch type.

Two types of batch furnace have been used for this duty, the hearth, or ' in-and-out ' furnace, and the pit furnace. By far the greater amount of steel is heated in hearth furnaces, but they are not suitable for very heavy slabs because of the difficulty of handling these with normal charging machines. When the slab weight is more than 10–12 tons, or when the physical dimensions of the piece place it beyond the range of the charging machine and/or hearth furnace, a pit-type furnace is generally used. If the number of large slabs to be rolled does not justify the provision of a separate unit, the slabs may be heated in one of the ingot soaking pits, provided that the plant layout allows the material to be handled satisfactorily.

The first hearth furnaces were of the Siemens regenerative type, fired with raw gas from central producer plants, although coal-fired furnaces equipped with waste-heat boilers were also used. With the former, the long gas mains were a definite handicap, as they had to be maintained and kept clean and, in addition, there was always a considerable loss of sensible heat and condensible constituents. To overcome these difficulties, Siemens brought out his ' New Form ' regenerative furnace, in which each unit had its own built-in producer plant.[31] This design ensured a supply of hot, rich gas at the furnace and obviated the necessity for gas regeneration. Many furnaces of this type functioned very satisfactorily in plate mills, but the problem of supplying fuel to a number of units and disposing of the ashes, coupled with the improvements in the design, layout, and operation of centralized gas plants and distribution systems, led to this design being gradually abandoned.

As with ingot heating furnaces, modern slab furnaces differ from the early installations mainly in their more robust construction, use of higher quality refractories and insulation, improved design of mechanical parts, and greater hearth area. Basically the furnaces are the same, and it is interesting that the system introduced by Siemens has maintained its position to the present day.

Slab Handling

Considerable changes have taken place in the methods of conveying the slabs to the reheating furnaces and thence to the plate mills.

In the early plants the slabs were delivered on hand bogies and transferred to and from the furnaces by means of levers and tongs, the same bogies then being used to carry the slabs to the mill. An alternative method was to carry the slab on a peel bar suspended by chains from an overhead telfer ; steam portable and hydraulic jib cranes were also used, although chiefly in conjunction with pit furnaces, for which they were well suited.

These methods sufficed when slab weights and outputs were small, but as these increased, additional mechanical assistance became necessary. The first electrically driven overhead slab-charging machine was installed in 1908 at the Mossend Works, and was quickly followed by other similar installations. All machines followed the same general design, although the mechanism for gripping the slab when lifting has been of two types. In the first system the gripping faces were horizontal, and held the slab by its top and bottom faces. The disadvantage of this arrangement was in picking up a slab from the floor, or from a pile when clearance was not available below the slab for the insertion of the bottom member of the tongs. Later machines were designed with side-gripping tongs which could engage the edges of the slab, and therefore had a far wider application. The capacity of charging machines has not varied greatly, the maximum size of machine used being about 12 tons.

Plate Mills

In contrast to slabbing mills, which were specially developed for rolling steel, the early plate mills copied those already in use in the wrought-iron industry. With one exception, every known type of plate rolling mill has been or is being operated in Scottish works ; no mill having the 4-high arrangement of rolls has yet been installed.

To the uninitiated, the rolling of a flat plate may not appear to present any serious problems and it might be expected that the plant required for the purpose would be of a comparatively simple nature. Nevertheless the conditions imposed are extremely onerous, and various types of mill have been used to ensure the most satisfactory results.

The essential requirement of a plate-rolling mill is that it should roll all plates within its capacity accurately to gauge and with a high standard of surface finish, even when producing plates of minimum thickness and maximum width and length. It must also be capable of rolling at high speed, to ensure maximum output when dealing with light-weight slabs, and quick reduction to finished gauge to minimize heat loss

and so satisfy the requirements for surface finish.

Not every mill has been completely satisfactory in all respects, but many have attained a considerable measure of success. By evolutionary changes, later installations have avoided some of the weaknesses of earlier mills ; consequently, those now operating have very high standards of performance.

Reference has already been made to the different types of plate mill that have been used in works in this area ; these differ mainly in the roll assembly, the number of roll stands, and whether the rolls run continuously in the same direction or are reversed after each pass.

Two-Stand Two-High Continuously Running Pull-Over Mill—This early type of mill, which was only suitable for the production of light plates, consisted of two stands of 2-high rolls, 22 in. to 26 in. dia. × 5 ft. to 7 ft. long, driven by means of a continuously running steam engine through pinions and coupling spindles in the conventional manner. The slab or plate was passed between the rolls and returned over the top roll, all the work being performed manually with very little mechanical assistance. The pull-over mill is now used only for sheet rolling, and has been superseded by other types for plate production.

Two-Stand Two-High Reversing Mill—The next stage of development was the introduction of the reversing drive for mills of the type referred to above. This led immediately to greater outputs, by reducing the idle time at the rolls and eliminating the heavy manual effort required to lift the piece back over the top roll between passes.

Roll sizes have varied from 26 in. to 44½ in. dia. × 7 ft. to 14 ft. long, but as the number of wide plates has always been relatively small it has been usual, for the larger mills, to make the roughing rolls full width, and to limit the finishing rolls to a length suitable for dealing with the majority of plates. Many mills of this type have been installed, and two such units are still in operation.

Single-Stand Lauth Three-High Mill—The first installation of a single-stand Lauth 3-high plate mill was made at the Blochairn works in 1888, but unfortunately its performance was disappointing, and it was closed down after a few years' service. Subsequently other and more successful mills of the same type were built, and one unit is still operating very satisfactorily. These mills had top and bottom rolls 28 in. to 36 in. dia. × 7 ft. to 9 ft. long, the diameter of the middle roll being usually about two-thirds that of the top and bottom rolls.

Single-Stand Two-High Reversing Mill—Where it has been necessary to roll wide plates in relatively small quantities, the single-stand 2-high reversing mill has sometimes been installed, as the initial outlay is less. The roll sizes for mills of this type have varied from 36 in. to 49 in. dia. × 12 ft. to 15 ft. long.

Two-Stand Two-High Tandem Reversing Mill—In rolling light and medium gauge plates the advantages of the 2-stand mill—so far as accuracy and surface finish are concerned—have often been strongly expressed. Loss of heat, when transferring the partially rolled plate from the roughing to the finishing stand, is a drawback, however, and the introduction of a tandem reversing mill at the Wishaw Works in 1906 was an attempt to eliminate this weakness without sacrificing other desirable features.

Single-Stand Two-High Reversing Universal Mill—Two mills of this type, having vertical edging rolls, have been installed. In addition to ordinary plates, they were well suited to the production of tube skelp and girder flange plates, for which there was a large demand in this area, but changes in manufacturing processes and policy led to the mills being abandoned.

What has been written about the constructional features of slabbing mills is also largely applicable to plate mills, as developments and improvements have followed the same general lines.

Prime Movers—The conditions under which plate-mill prime movers operate are difficult in the extreme, and no other form of rolling mill imposes such severe demands on its driving unit. The rolls may be run continuously, as in pull-over and 3-high mills, or intermittently, as in reversing mills ; but in all cases the prime mover must be capable of exerting sufficient power to deal with the maximum width and length of plate, even under the most unfavourable conditions of gauge and temperature.

Where the mill is continuously running, the prime mover can be a constant-speed medium-powered unit with one or two flywheels to assist in carrying the peak loads and gearing to reduce its speed to mill speed. If the proportions of the unit are correctly chosen, no serious difficulty need be anticipated, although there is one drawback which is common to all constant-speed rolling-mill drives. The choice of speed must be a compromise, as it must suit both roughing and finishing passes, and therefore will be high for the former and low for the latter. As a result the mill parts will be subjected to severe shock-loading during the early passes, and delays may be caused by the piece being thrown too far from the rolls ; similarly, time will be lost in the finishing passes because of the relatively slow speed of the mill.

Various types of prime mover have been used for continuously running mills, *i.e.*, twin-cylinder steam engine, gas engine, steam turbine, constant-speed electric motor and, to overcome the difficulties mentioned above, variable-speed direct-coupled electric motor. With the last-named unit it is possible to take the initial passes slowly and to increase speed as the piece lengthens ; the motor is also reversible, so that a piece can be more easily removed from the rolls in the event of a cobble.

With reversing mills the conditions to be fulfilled are much more severe. The driving unit must be capable of rapid acceleration and deceleration, to ensure speedy reversal, must be easily controlled, and also powerful enough to deal with the peak loads of the mill, as flywheels cannot be used.

As with slabbing mills, twin-cylinder simple non-condensing steam engines, direct-coupled for the lighter mills and geared for the heavier ones, were widely used in the early days. Later, the twin-cylinder tandem compound-condensing engine was introduced, and one very fine example of this type of machine is still in service. Triple-cylinder simple non-condensing engines were fitted to two mills, and these were among the last reversing engines to be built in Britain for mill duty. With the exception of

the unit already referred to for the 3-high mill, only one reversing electric drive has been installed for plate-mill duty.

Leading Couplings, Pinion Housing Units and Driving Spindles—The evolution of these items of plant has been the same as for slabbing mills. The higher speeds and heavier loadings encountered in plate mills have emphasized their importance, and all mills are now equipped with well-designed transmission systems.

In 2-stand reversing mills, usually both top and bottom rolls of the roughing stand are driven positively, whilst the bottom roll only of the finishing stand is so driven ; the top roll rotates by virtue of the frictional contact between it, the material, and the driven bottom roll. Where light gauge material is being produced, the rolls if positively driven must be perfectly matched in diameter, otherwise rapid wear of rolls and pinions may occur. This exact matching of rolls presents some difficulty, and the loose top roll offers a relatively simple, although not always effective, solution.

In fast-running mills, and especially those with efficient bearings, trouble is often experienced from ' roll spin.' The top roll, being free in its mountings, continues to turn after the material has left the mill, and where reversal is very rapid, as in steam-engine-driven units, the piece may be presented to the mill before the top roll has come to rest. When the piece is entered, the top roll must be halted and brought up to speed in the reverse direction by frictional contact through the piece from the bottom roll. This can impose shock-loadings of almost unpredictable magnitude on the mill parts, resulting in premature failure of items such as bearings and rolls. To minimize this very serious disability, a simple type of brake may be fitted to the offside end of the top hard roll ; this is no more than a partial cure, however, as it only stops the roll, which must still be set in motion by the bottom roll through frictional contact with the piece.

A more positive method is to provide a light type of pinion housing on the offside of the finishing stand, the bottom roll being connected to the input shaft of the gear by means of a spindle, whilst a similar spindle connects the output shaft to the top roll. An adjustable plate-type friction coupling, which allows slip to take place if the rolls are not exactly matched, is built into the top pinion.

Roll Stands—The most important requirement of any plate-mill roll stand is stiffness ; if this is lacking, all other features, however desirable in themselves, cannot make good the deficiency. To ensure this condition the roll housings must be of steel, with ample cross-sectional area in the posts, and minimum window width and height commensurate with operational requirements. In addition to the housings, all other parts such as screws and nuts must be of generous proportions, to minimize stretch and consequent variation in plate gauge.

In view of the very heavy loadings encountered in plate mills, and the high rolling speeds involved, the design of the roll-neck mountings is of particular importance. As in slabbing mills, the multi-part brass bearing has been superseded by the white-metal-lined steel-shell bearing, but complete success has not yet been achieved. However, the improvements in performance, so far as power consumption and accuracy of product are concerned, have been considerable.

Originally the top roll was adjusted by hand, but this motion was soon mechanized and steam engines were introduced for the duty, later to be superseded by electric motors ; in view of the short distances and high degree of accuracy required, screwing speeds are relatively low. The pressure pads between the screws and the chocks are designed as breaking members, to safeguard the housings and rolls in the event of overloading. They are generally of cast iron with a steel wearing piece which can be forced through the iron portion under conditions of extreme loading.

Rolls—Rolls for plate mills are subjected to exceptionally severe duty, and to satisfy operating conditions they must have a hard surface and a tough core, and must be resistant to heat and the abrasion caused by slip between the rolls and the material.

For the most part, these requirements have been best met by the use of grain cast iron for the roughing rolls and chilled cast iron for the finishing rolls ; for this reason these rolls are still referred to as ' soft ' and ' hard ' rolls respectively. More recently, alloy cast steel has given good service in roughing stands, although chilled cast iron is also being used successfully.

The contour of the roll is an important factor, influencing the accuracy of gauge, and is determined, among other things, by the stiffness of the rolls and mill parts, type and quality of product, whether the rolls are run wet or dry, and the rolling practice.

Roller Tables and Manipulating Devices—The demand for more and heavier plates hastened the development of equipment for handling the slabs at the mill. So long as plates were comparatively small the slabs could be conveyed from the reheating furnaces to the rolls on hand bogies and there dealt with manually, the procedure being arduous and often dangerous.

Power-driven roller tables were then installed, and, for 2-stand mills, rope-hauled transfer carriages which moved the partially rolled plate from the roughing to the finishing stand. At a later date, fixed roller tables were installed at both stands, and rope- or chain-driven skids were used to manipulate the piece from one stand to the other.

The treatment which plate-mill roller tables (particularly those serving the roll stands) undergo is very severe. Operational requirements are difficult to fulfil, and the design of equipment for this duty presents many problems, as slab sizes usually vary within wide limits. Small pieces must frequently be rolled, and this necessitates the provision of closely pitched rollers capable of feeding between the housings and up to the rolls. Special precautions must also be taken to enclose and lubricate the bearings and driving gears, and to exclude scale and water, problems which are aggravated by the use of high-pressure water for scale removal.

The tables adjacent to the mill are often subjected to exceptionally heavy loading as the piece leaves the

rolls. Where the heating practice is not good the slabs tend to curve upwards or downwards; in the latter case, blows of considerable magnitude can be inflicted on the table elements and, if persistent, may lead to breakages. Their effect can be minimized by maintaining the correct height relationship between the tops of the rollers in the tables and the mill rolls. Collared or interlocking rollers are also frequently used close to the mill, as they enable large diameter rollers to be accommodated at close centres, and more generously proportioned bearings and gears can then be used without difficulty.

In many of their features, tilting tables for 3-high mills conform to the same general designs as tables for 2-high mills. The tables are balanced hydraulically, hydro-pneumatically, or by weights, and are operated electrically or hydraulically. Their movement is synchronized with that of the middle roll, *i.e.*, as the roll moves upwards the tables move downwards, and *vice versa*.

To facilitate the manipulation of the piece on the working roller tables, the turning gear and the centring gear have been developed. In normal practice the slab is first rolled to a length approximating to the finished width of the plate, then turned through 90° and rolled down to gauge. Originally, the turning motion was imparted to the slab by dropping a pin into one of a series of holes in a deadplate on the entry side of the mill. This engaged the leading edge of the slab eccentrically, and operation of the roller table caused the slab to turn about the pin. The pin was inserted by hand, but subsequently a number of small cylinders were fitted into the table so that the pin could be raised and lowered hydraulically; this permitted the slab to be turned without manual assistance.

For producing plates that are as nearly rectangular as possible, the piece must be presented to the rolls squarely and centrally. This is assisted by mechanical equipment, which may be of the self-centring type, where operation of the gear automatically brings the piece into the desired position, or the pusher type, where independently driven pushers or skids are used. The former is generally fitted to single-stand mills or on the ingoing side of 2-stand mills, whilst the latter is used on the outgoing side of 2-stand mills, where it also serves to transfer the piece from one stand to the other.

The roller tables for conveying the plates from the mill and through the various stages of the finishing processes are as important as the main working tables, although they are not so heavily loaded. Many design requirements are common to all, *i.e.*, enclosure and lubrication of bearings and gears, ample clearance between tops of rollers and machine parts on each side of the rollers, well fitted deadplates, and avoidance of openings or projections which might be troublesome when handling plates with irregular ends. If the tables are dealing with hot plates, the pitch of the rollers must not be excessive, as any delay may cause the plates to sag between rollers, thus necessitating special flattening when cold.

Flattening of Plates

The degree of flatness which it is possible to attain is largely determined at the rolling mill itself. The heating of the slabs and the condition, contour, and setting of the rolls are important factors that influence the quality of the plate, and any faults arising from these causes are difficult to eliminate. Roll wear and deflection or uneven expansion of the rolls may result in plates of uneven gauge with fullness in the centre or on the sides. These faults will always persist to a greater or lesser degree, and every precaution must be taken to prevent them reaching a stage where they become difficult to correct by subsequent processing.

Plates can be flattened in the hot or cold state, and for obvious reasons it is desirable that they should be dealt with in the former condition. The most convenient arrangement is one which permits flattening to be effected at mill heat, and the equipment should therefore be provided in tandem with the mill. Cold flattening is usually resorted to if specially flat plates are required, or when the normal standard cannot be attained because of difficulties at some intermediate stage of manufacture.

Hot Flattening—Except for a relatively small quantity of armour and heavy plates, which may be press flattened, all hot flattening is effected on mangles. On these machines the plate is passed one or more times between two nests of rollers, the upper nest being offset one-half roller pitch relative to the lower nest. By suitably adjusting the top nest of rollers, the plate can be flexed across the width during its passage through the machine, the number of corrugations and their size depending upon the number and setting of the rollers. Paradoxically, it is this bending of the plate in reverse directions by regular but diminishing amounts that gives the flattening effect.

To ensure satisfactory performance of the hot mangle, the roller size and spacing must be the minimum commensurate with the thickness and tensile strength of the material to be flattened, and all work rollers must be positively driven. Other desirable features are that the first rollers at the entry and delivery sides of the machine should be separately adjustable, and that all work rollers should be arranged for internal water cooling. Particularly important is the provision of facilities for dealing with the scale which is loosened from the plates during the flattening process.

Only in the more recently installed machines have any serious attempts been made to satisfy all these requirements. The early machines had two top and three bottom rollers, the latter driven by steam engine through reduction gearing, but subsequent machines were electrically driven and had five top and four bottom rollers. However, it was not until the close-pitched small-roller machine, with backing rollers for supporting the work rollers, was introduced that really efficient flattening became possible. Most plates are now mangled on machines of this type, which give a very high standard of flatness.

The movement of plates from the mill to the hot mangle was originally by means of hand bogies and later by winch and wire rope, but with increasing mechanization driven roller tables came into use and quickly superseded the more primitive methods. The hot mangle is now located relatively close to the

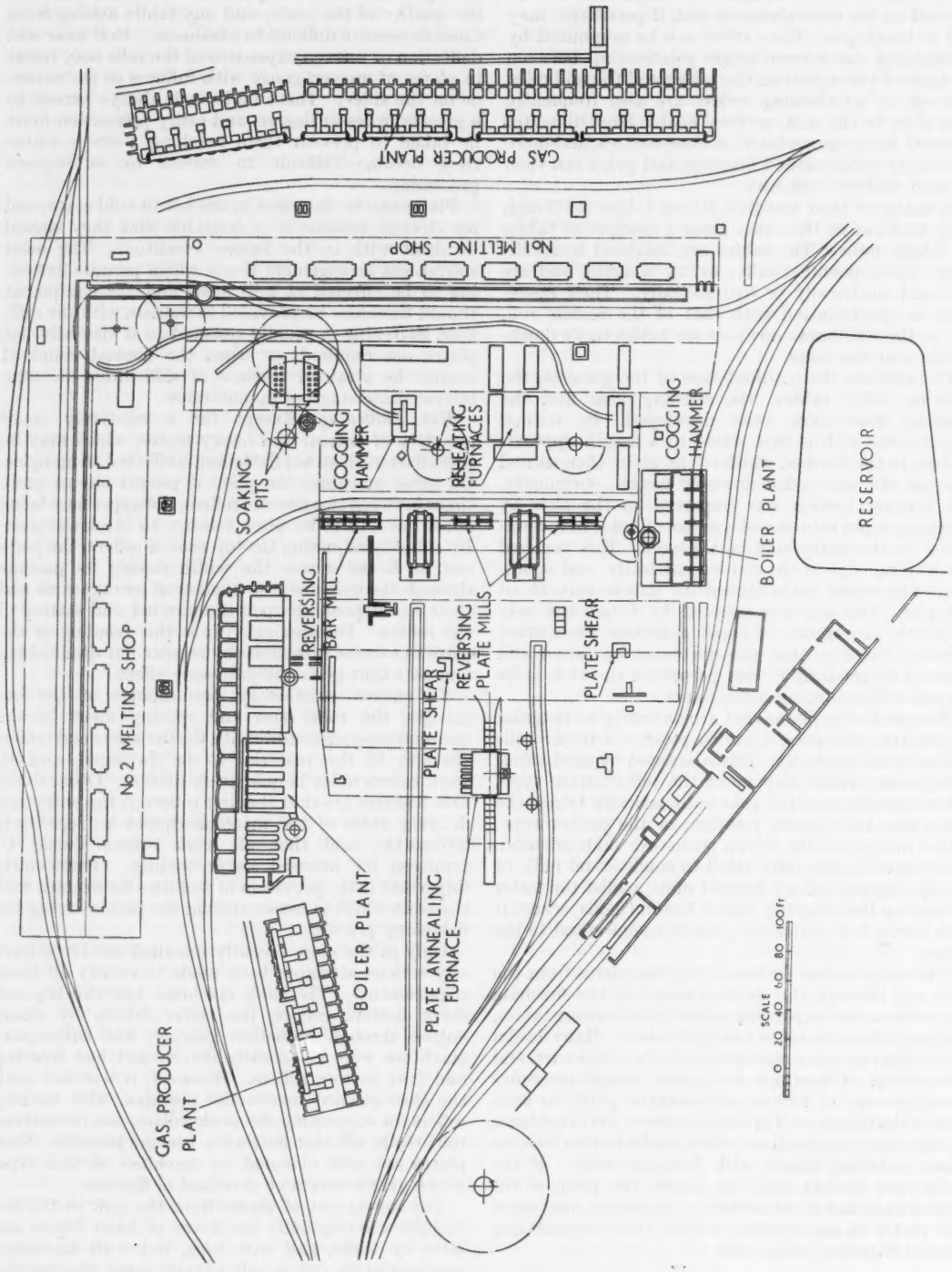


Fig. 6—Dalzell Works. Layout of works in 1890

finishing rolls, and all plates are processed on their way to the cooling banks.

Cold Flattening—The introduction of improved plant and methods for hot mangling has resulted in a decrease in the need for cold flattening; nevertheless, specially flattened plates are still specified for particular applications. Mangles, generally of similar construction to the hot machines, are provided, although in view of the smaller tonnages normally handled they can be of somewhat simpler construction.

If plates beyond the capacity of the mangles are to be flattened, they can be dealt with on hydraulic presses, but this is a slow and expensive procedure and should be adopted only if absolutely essential.

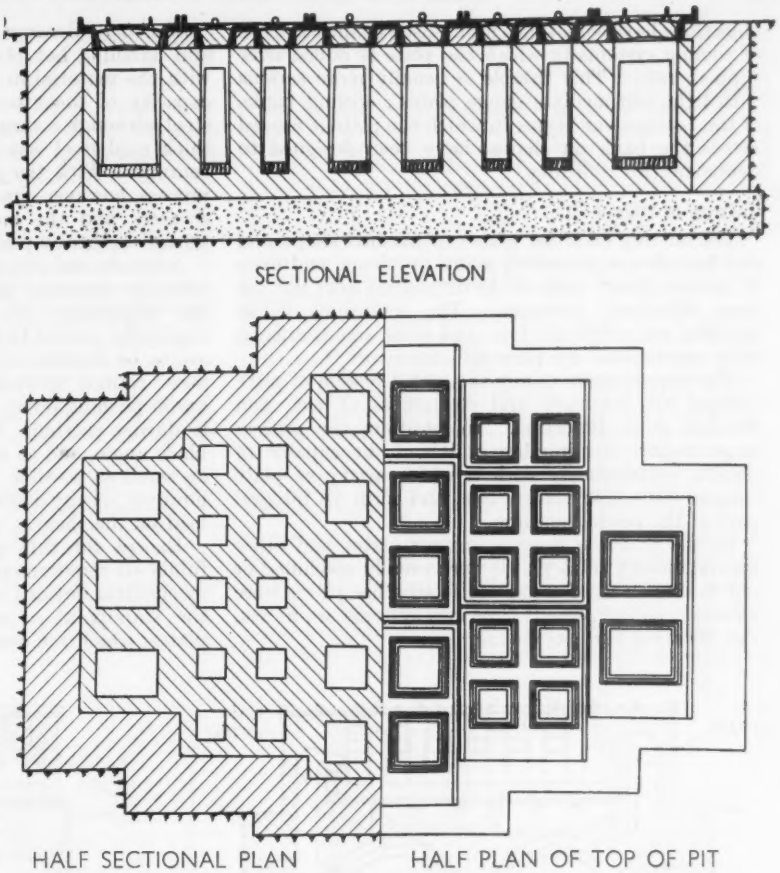


Fig. 7—Dalzell Works. Arrangement of dead soaking pits. (Scale, $\frac{1}{8}$ in. = 1 ft.)

Cooling of Plates

After the plates leave the rolls they must be allowed to cool in such a way that their flatness and surface finish are not impaired. In all cases the plates are laid out on a flat surface called the cooling floor, cooling bank, or cooling bed. This cooling area must be sufficiently large to cope with the mill output at the maximum rate of production, and the plates, irrespective of thickness, must be permitted to lie on it long enough to attain a temperature at which they can be inspected, marked out, and cut to size. It must also be constructed so that the plates will not distort during cooling nor the surfaces of the plates be damaged while being moved across it.

Various types of cooling floor have been used, and those now operating have been evolved to deal with the production of high-capacity mills.

In the early mills the plates were taken from the rolls on bogies and were deposited on the floor to cool. This was covered with plain or perforated cast-iron plates, and for cooling effect relied almost entirely on radiation from the upper surface of the rolled plates. As sizes and weights increased, some change in the method of handling the plates from the mill became necessary, and power-operated capstans with wire ropes were then used to pull them on to the floor.

The next stage of development was the introduction of a fully mechanized bank at the Mossend Works in 1908. This consisted of rails arranged at close centres and supported on brackets, the space below being open to allow free air circulation for cooling. The plates were delivered from the mill on a driven roller table, and were removed therefrom to the bank located alongside by means of rope skids; these skids also pulled the plates across the bank, during which time they cooled and were marked out for shearing. Turnover gear, which allowed both sides of the plates to be inspected for surface defects, was installed in the bank and the shearing equipment was arranged in series with the bank. This installation was one of the first of its kind in Britain, but unfortunately considerable time elapsed before other plate makers in Scotland followed the example.

The next installation was made at the Clydebridge Works in 1923, but it differed slightly from the earlier plant. The skids were of a somewhat novel design, consisting of rectangular magnets which were moved across the bank in the normal manner by ropes, and were energized at will by the operator from the control cabin, thus allowing the engagement of plates for skidding over. With this arrangement the bank could easily be filled and then emptied without labour on the floor, as the magnets were free to pass under or engage the plates as required. This system did not prove very successful in operation, and it was replaced by the dipping-finger type of skid gear in which similar results were obtained by mechanical means.

Reference has already been made to the importance of avoiding scratching or marking of the plates, and

objections have sometimes been raised against the use of cooling systems in which the plate is pulled over support rails. This trouble is usually more serious with light and medium gauge plates ; cooling banks of the ' carry-over ' type, in which the plate is moved across the bank on chains, have been designed to overcome this difficulty.

Cutting of Plates

The cutting of rolled plates to finished shape and size has always presented many problems, and even in modern plants some of the difficulties have not yet been effectively overcome. The conditions to be satisfied are relatively few, and their significance is fully appreciated by plate-mill operators.[32]

The requirements of any successful system of plate cutting are accuracy and cleanliness of cut, and freedom from distortion. In addition, the process must require a minimum of labour, be capable of dealing satisfactorily with a wide variety of plate shapes, sizes, and thicknesses, and form an integral part of the production line.

In the past the heavier armour plates and other special quality thick plates were usually machined or cut to size on band saws, whilst all other plates were sheared ; at the present time two systems are in use, *i.e.*, shearing and gas cutting.

Shearing—Because of the difficulties of marking and handling hot plates, all shearing is carried out with the material in the cold state. The maximum capacity of shear normally used is 2-in. thick mild steel, although a shear capable of cutting up to 2¼-in. thick mild steel was built in the nineties of the last century. With the development of the gas-cutting process, however, few plates over 1½ in. thick are now sheared, and the modern tendency is to abandon shears for heavy plate cutting.

Accurate and clean cutting is only possible with a correctly designed and properly maintained shear ; the importance of blade condition and setting, especially, cannot be over-emphasized. Where plates are to be divided or split, some distortion or ' shear bow ' cannot be avoided, as it is caused by the top apron pushing down the section of plate lying below it during cutting. The amount depends upon the blade angle, and to minimize its effect this should be as small as possible. There are practical limitations, however, as any decrease in the angle will increase the load on the shear.

Except for this question of distortion, shearing fulfils all requirements if advantage is taken of the mechanical devices which are now available. From the standpoint of cost and excluding the thicker plates, which are usually small in number and would

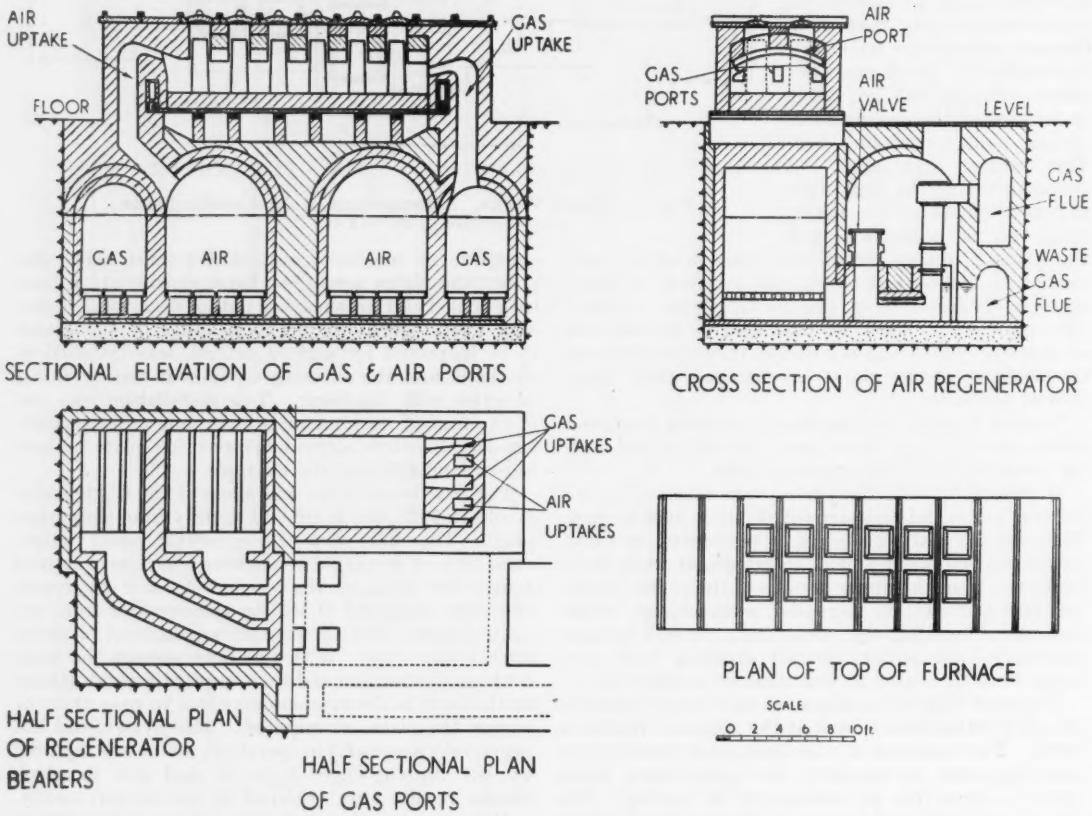


Fig. 8—Dalzell Works. Arrangement of vertical ingot heating furnace

not justify the installation of the heavy plant required to deal with them, shearing is the cheapest method of cutting plates which has yet been developed.

There are two types of plate shears, guillotine or cross-cut shears, and rotary-blade shears. Of these the first has always had the widest application, and at the present time is used exclusively in Scottish works.

(*a*) *Guillotine or Cross-Cut Shears*—In comparing the earliest shears of this type with their more modern counterparts, little change in the basic principles of design is to be observed. However, the use of better materials, increased size of working parts, higher standard of finish, and better lubrication and enclosure of gears, has resulted in considerable improvement in performance.

In addition, methods of driving the shears have been modified from time to time. The type of drive should be such that it would not be possible to overload the shear, and from this standpoint the hydraulic system of power transmission is ideal ; it is still used exclusively for heavy duty shears.

The first machines were driven by means of one or two steam engines through reduction gearing to the camshaft ; but shortly afterwards, hydraulically operated lever-type shears, working on low- and medium-pressure water, were introduced, and proved highly successful. At a later date these shears were constructed with hydraulic intensifiers, which gave increased capacity but still allowed them to operate on the works' supply system. Finally the electrically driven shear was adopted, but its use has been limited, so far, to light and medium thickness plates.

Satisfactory performance of the guillotine type of shear is largely dependent on its design features. The cutting angle should be as small as possible and the blades, which must be easily renewable, should be capable of adjustment to give correct clearance between their vertical faces ; for the same reason, the guides of the top apron must be adjustable. The shear must be provided with a power-operated clamping or holding-down gear designed to grip the plate close to the cutting line, but no hydraulic cylinders, pipes, or valves should be located above the cutting line, as any water leakage tends to wash away the marking lines on the plate. The back of the shear, where not mechanically served, should be open to allow easy access for the removal of divided plates and of scrap.

(*b*) *Rotary Blade Shears*—The rotary-blade type of shear has a very limited application, and has rarely been used in Scottish works. It is well suited to side trimming and splitting of light and medium gauge plates, and when operated in conjunction with cross-cut shears can give very satisfactory results. It lacks flexibility, however, and if plates of considerable variation in width have to be dealt with, operational difficulties may be expected. Only once has such a shear been installed ; this was to serve a mill of rather special design, rolling a product of fairly uniform width and thickness.

Perhaps the most difficult problem encountered when shearing plates is in their manipulation. So long as mill outputs were low and supplies of labour plentiful and cheap, manual efforts sufficed. The plates were brought to the shear on bogies and manipulated during the shearing process by a large squad of

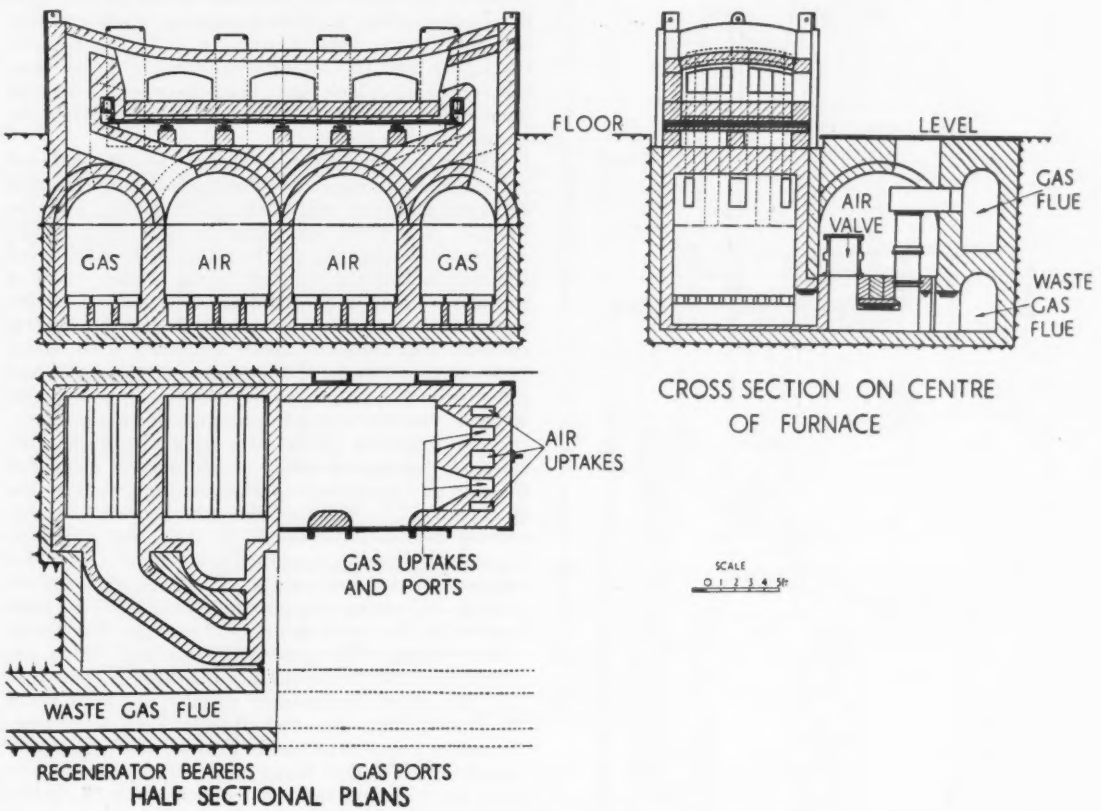


Fig. 9—Dalzell Works. Arrangement of slab reheating furnace

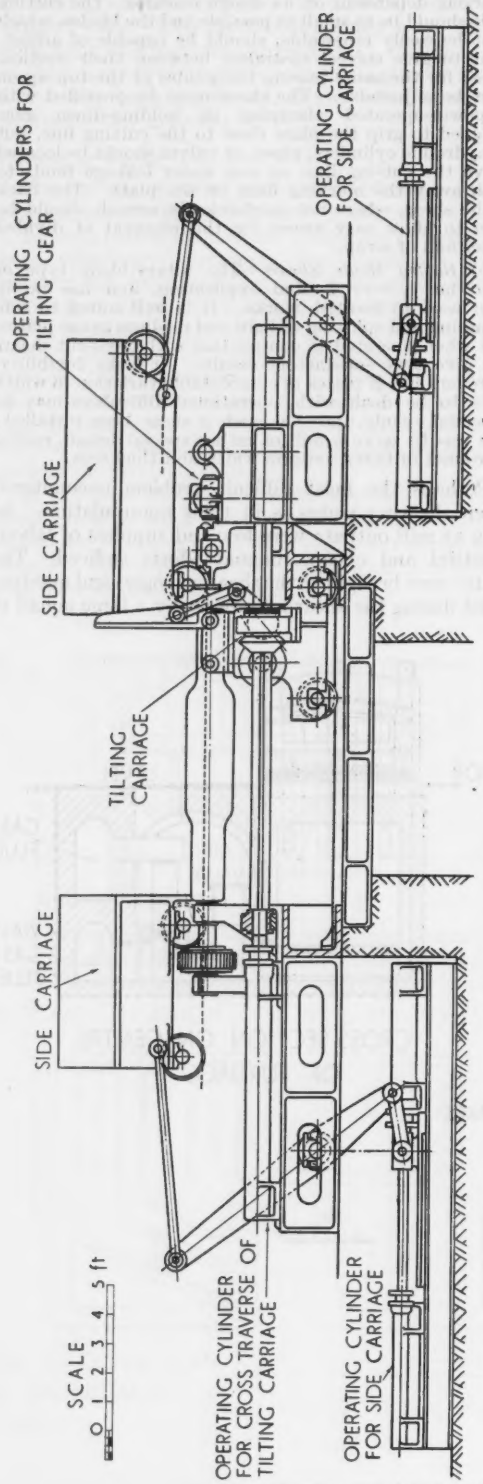

OPERATING CYLINDERS FOR TILTING GEAR
OPERATING CYLINDER FOR SIDE CARRIAGE
SIDE CARRIAGE
TILTING CARRIAGE
SIDE CARRIAGE
SCALE
0 1 2 3 4 5 ft
OPERATING CYLINDER FOR CROSS TRAVERSE OF TILTING CARRIAGE
OPERATING CYLINDER FOR SIDE CARRIAGE

Fig. 10—Dalzell Works. 33 in. × 8½ ft. reversing slabbing mill; cross-section through manipulator and working roller table

men with forks. In some cases crane assistance was available ; nevertheless shearing remained a tedious and expensive business.

As the technique of rolling improved, outputs and the size and weight of individual pieces increased, and some change in the method of handling the plates at the shears became necessary. Castor beds were introduced, and this simple device helped considerably in easing the work of manipulation. Unfortunately, the number of men was not greatly reduced and alternative solutions to the problem were sought. The first workable proposal to mechanize plate handling during shearing was made in 1901, when designs were prepared and orders actually placed for a shearing table for the Dalzell Works. This unit consisted of a number of driven rollers, mounted on a carriage which could be power-traversed past the shear in a line parallel to the blades. A number of air-operated clamps were arranged between the rollers, and these could be moved across the table by means of electrically driven screws. Thus it was possible to carry the plate along parallel to the blades, or to adjust it towards or away from them. For some reason this table was never completed, and it was not until 1923 that the same idea was re-introduced into Scotland. This was the Ennis table, which differed from its earlier counterpart only in that the plate was held by means of magnets instead of air clamps. Two tables of this type were installed in conjunction with fixed roller tables, to serve a cross-cut shear and two side-cut shears, thus forming a fully mechanized cutting-up line. In a later development of this system, the travelling tables have been dispensed with and fixed roller tables have been used for conveying the plates past the shears.

Within the capacity of the shears, these mechanized cutting lines are capable of dealing satisfactorily with all rectangular or near rectangular plates, and are limited, in a downward direction only, to a length and width determined by the pitch of the rollers and the approach of the magnets to the blades ; most of the plates made in Scotland are now sheared in this manner. Some plates cannot be dealt with by this method, and separate shears equipped with castor beds are provided for the purpose ; sketch plates and others which it would not be desirable or practicable to shear elsewhere, are finished on these machines.

Some reference should also be made to the considerable tonnage of scrap, which must be cut either for sale as ' marketable scrap ' or for return to the steel plant. In some cases the main shears have scrap-cutting devices incorporated in them, but small independent shearing machines are generally provided adjacent to the main shears. These scrap shears are capable of cutting the maximum thickness of plate handled at the main shears, and also cut test pieces.

Gas Cutting—The gas-cutting process, which was introduced into steelworks a comparatively short time ago, has grown increasingly popular in recent years. Its development has undoubtedly been accelerated by military requirements for armour and bullet-proof plates, but it is now being used very extensively for mild steel, particularly in connection with welded fabrications where a clean edge is desired.

It is beyond the scope of this paper to deal compre-

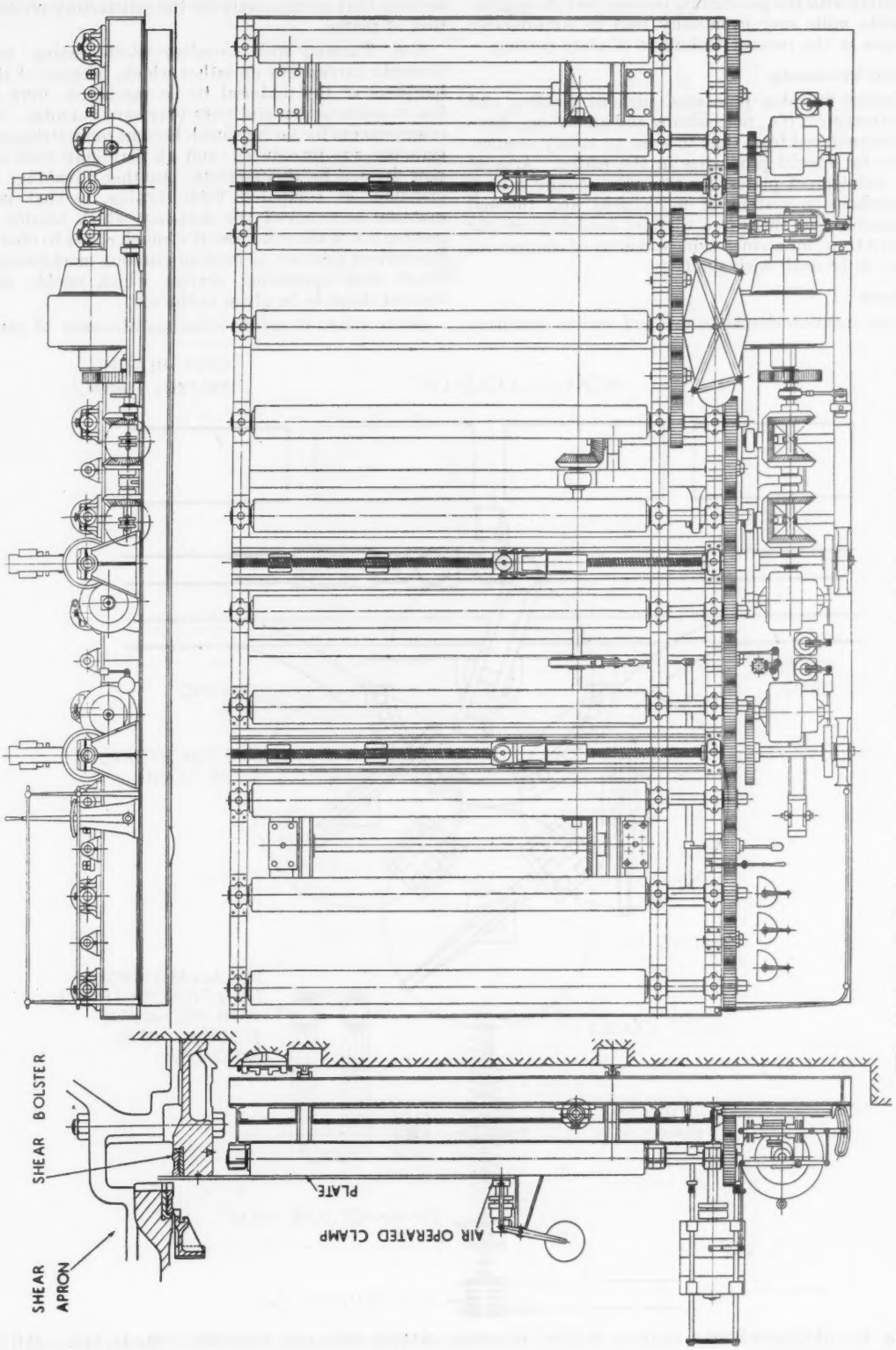


Fig. 11—Dalzell Works. Arrangement of mechanical shearing table. (Scale, $\frac{1}{8}$ in. = 1 ft.)

hensively with the gas-cutting process, but its applica- to plate mills may eventually lead to considerable changes in the present technique of plate cutting.

Special Processing

Various finishing processes, such as pickling and heat-treatment (*i.e.*, normalizing and annealing), have been introduced from time to time, to satisfy requirements for special properties in the plates. Armour and bullet-proof plates, for example, require a very comprehensive system of mechanical and thermal treatment, and there is a distinct tendency, at the present time, for an increasing quantity of commercial plates to be dealt with similarly.

Services

Some mention should be made of various auxiliary services that are necessary for the satisfactory production of plates.

Roll Turning and Grinding—Roll-dressing was formerly carried out on lathes which, because of the hardness of the material to be machined, were of heavy construction and were very slow running. As requirements for surface finish became more stringent, grinding was introduced, and all plate-mill rolls are now dressed by this method. Another advantage of grinding, as compared with turning, is that less material is removed per dressing, which results in greater life of the roll. Also it is much easier to obtain the correct contour, as modern grinding machines are fitted with cambering devices which enable any desired shape to be given to the roll.

Shear Blade Grinding—The maintenance of plate

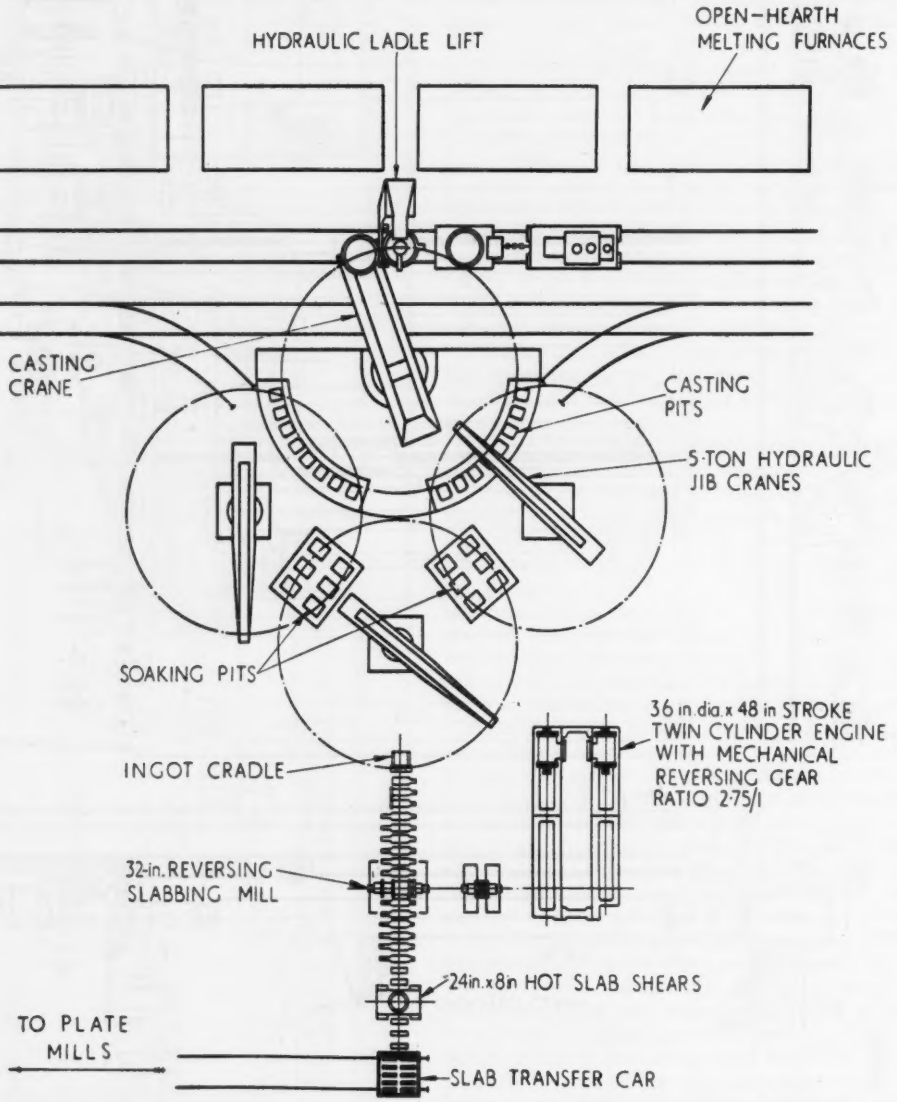

HYDRAULIC LADLE LIFT
OPEN-HEARTH MELTING FURNACES
CASTING CRANE
CASTING PITS
5-TON HYDRAULIC JIB CRANES
SOAKING PITS
36 in. dia. x 48 in STROKE TWIN CYLINDER ENGINE WITH MECHANICAL REVERSING GEAR RATIO 2·75/1
INGOT CRADLE
32-in. REVERSING SLABBING MILL
24in. x 8in HOT SLAB SHEARS
TO PLATE MILLS
SLAB TRANSFER CAR

Fig. 12—Blochairn Works. Layout of 32-in. reversing slabbing mill plant, built 1885. (Scale, 1 in. = 25 ft.)

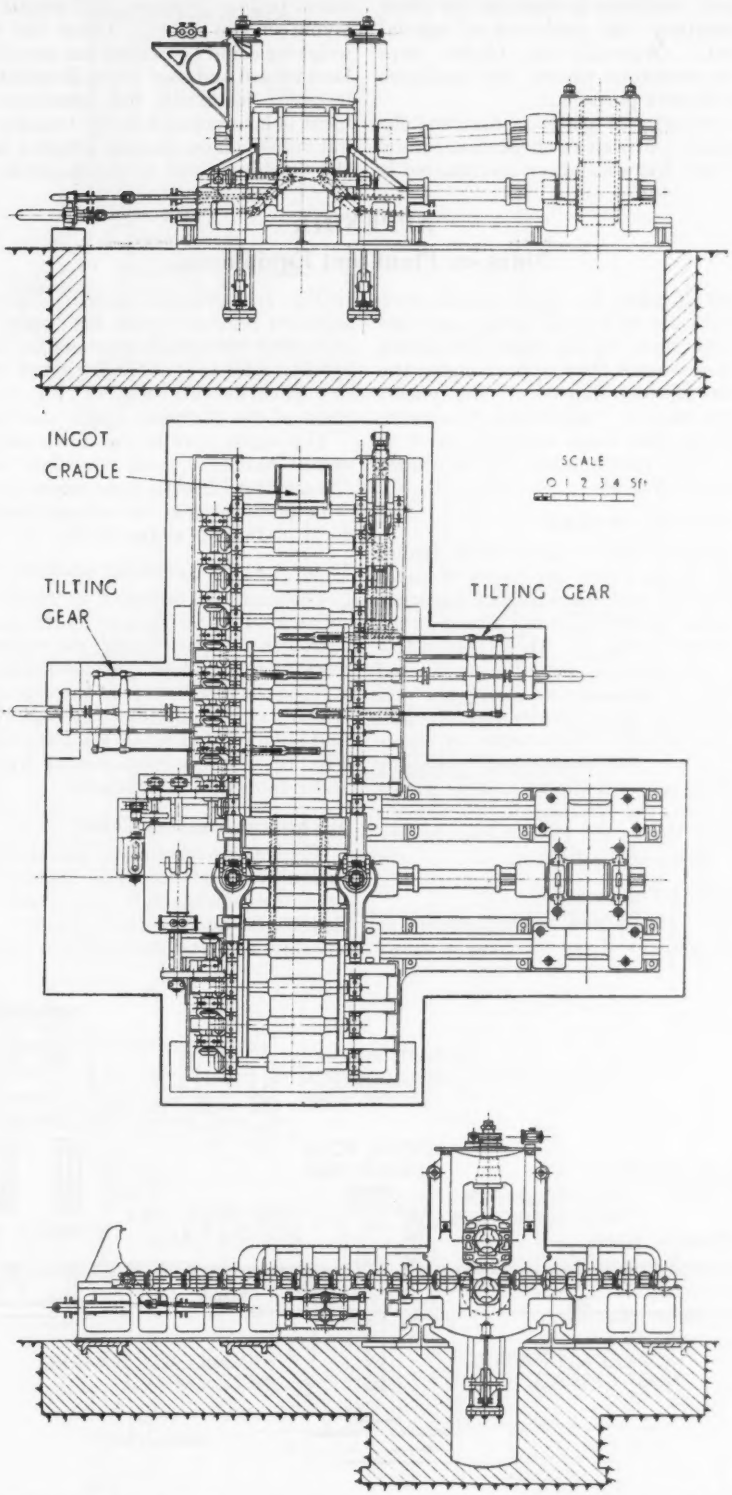


Fig. 13—Blochairn Works. Arrangement of 32-in. reversing slabbing mill, built 1885

shear blades in good condition is essential for clean cutting, and necessitates the provision of special grinding equipment. Originally the blades were ground by hand on sandstone wheels, but machines are now available for this purpose.

Weighing—The weighing of plates is essential for book-keeping purposes, and is also a check on accuracy of rolling. Before mill floors had been mechanized it was a tedious business, and meant much lifting and laying of the plates. Often the only place where weighing could be carried out was after the plates had been loaded and were being dispatched over the works weighing machines, but nowadays weighing equipment is incorporated in the transfer roller tables, and individual plates can be weighed as they pass from the finishing plant to the dispatch department.

APPENDIX

Notes on Plant and Equipment

The development of plant for plate manufacture has been covered already in general terms, and this Appendix deals with some of the more interesting items ; for ease of reference they appear under the heading of the works in which they occur. Equipment still operating in the Dalzell, Clydebridge, Blochairn, and Parkhead Works has been omitted, as it is intended to study these plants more fully in a later paper on present-day methods.

DALZELL WORKS

These are the parent works of the Colville Group of Companies, and are the oldest producers of plates for commercial purposes now operating in Scotland. Plates were first rolled in 1880, and the layout of the works in 1890 is shown in Fig. 6. Those responsible for the works' direction have consistently anticipated developing demands, particularly so far as the size and weight of individual plates are concerned, and equipment has always been chosen with an ample reserve of capacity to meet customers' increasing requirements. With the exception of those plants devoted primarily to the production of armour material, the Dalzell Works roll the heaviest ingots, slabs, and plates, produced in Britain.

Ingot and Slab Heating Equipment

Gjers, or ' dead ' soaking pits, were installed in 1889, and the arrangement of one of these is shown in Fig. 7. Although the pits were satisfactory when supplied regularly with hot ingots, the difficulty of operating the open-hearth melting shop to ensure this condition led to the installation of ' live ' soaking pits, or vertical heating furnaces ; Fig. 8 shows the arrangement of one of these, which was built in 1890.

The ingots were forged down and cut to size under steam hammers, and the slabs were reheated in ' in-and-out ' hearth type regenerative furnaces fired with producer gas ; the arrangement of one of these, built in 1880, is shown in Fig. 9.

33 in. × 8½ ft. Reversing Slabbing Mill

This mill was installed in 1894, and was the first of its kind to be equipped with power-operated side carriages for positioning the piece laterally on the working roller tables. These can be considered, therefore, as the forerunners of the side guard manipulator, which was introduced at the beginning of the century and is now fitted to all blooming and slabbing mills ; Fig. 10 shows a cross-section through the working roller table and manipulator.

Mechanical Shearing Table

The cutting-up of plates has always presented many difficulties, particularly in the early days when little or no mechanical aids were available and all plates had to be dealt with manually. The first serious attempt to solve this problem of manipulation was

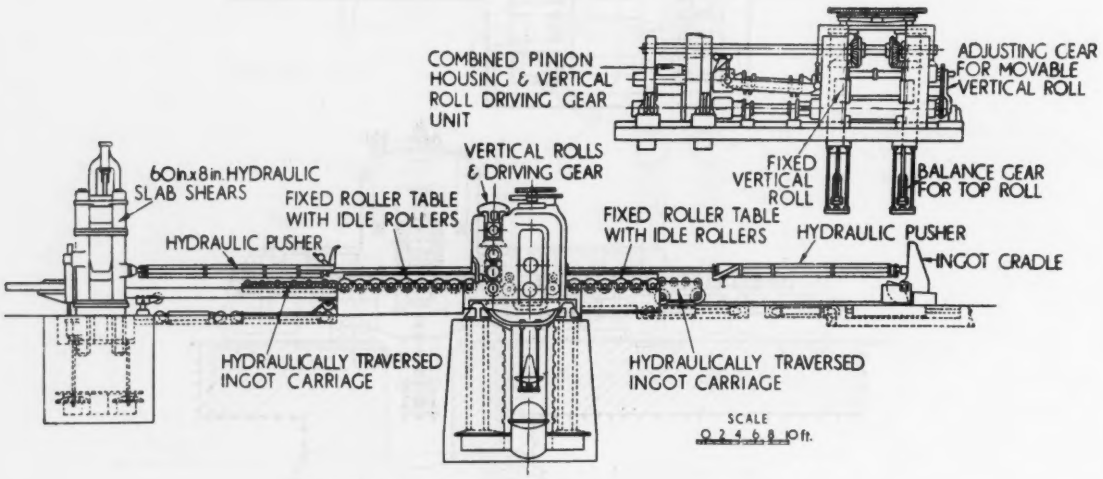

COMBINED PINION HOUSING & VERTICAL ROLL DRIVING GEAR UNIT
ADJUSTING GEAR FOR MOVABLE VERTICAL ROLL
VERTICAL ROLLS & DRIVING GEAR
60in.x8in. HYDRAULIC SLAB SHEARS
FIXED ROLLER TABLE WITH IDLE ROLLERS
HYDRAULIC PUSHER
FIXED VERTICAL ROLL
BALANCE GEAR FOR TOP ROLL
FIXED ROLLER TABLE WITH IDLE ROLLERS
HYDRAULIC PUSHER
INGOT CRADLE
HYDRAULICALLY TRAVERSED INGOT CARRIAGE
HYDRAULICALLY TRAVERSED INGOT CARRIAGE
SCALE
0 2 4 6 8 10 ft.

Fig. 14—Blochairn Works. Arrangement of reversing universal slabbing mill

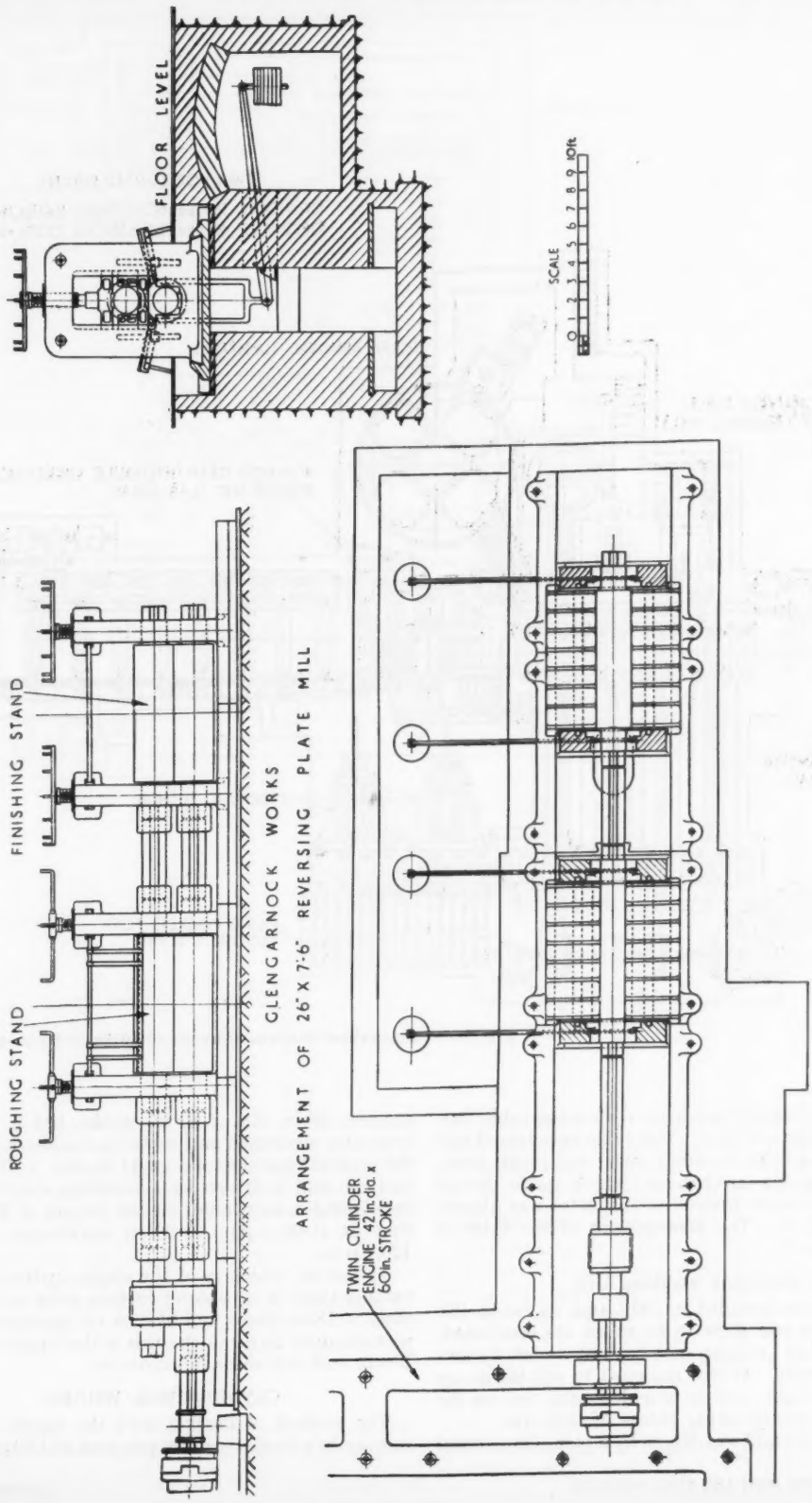

FLOOR LEVEL
SCALE
0 1 2 3 4 5 6 7 8 9 10ft
FINISHING STAND
ROUGHING STAND
GLENGARNOCK WORKS
ARRANGEMENT OF 26" X 7'-6" REVERSING PLATE MILL
TWIN CYLINDER ENGINE 42 in. dia. x 60in. STROKE

Fig. 15—Glengarnock Works. Arrangement of 26 in. × 7½ ft. reversing plate mill

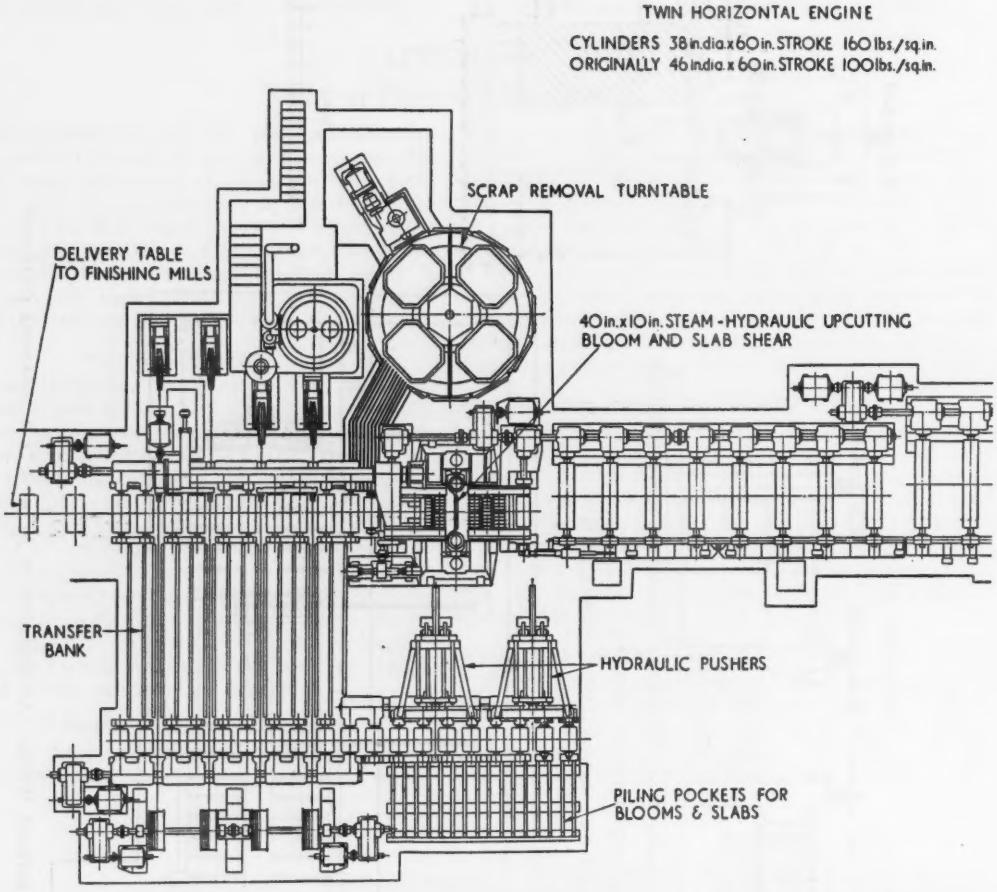

TWIN HORIZONTAL ENGINE
CYLINDERS 38 in. dia. x 60 in. STROKE 160 lbs./sq. in.
ORIGINALLY 46 in. dia. x 60 in. STROKE 100 lbs./sq. in.
SCRAP REMOVAL TURNTABLE
DELIVERY TABLE TO FINISHING MILLS
40 in. x 10 in. STEAM-HYDRAULIC UPCUTTING BLOOM AND SLAB SHEAR
TRANSFER BANK
HYDRAULIC PUSHERS
PILING POCKETS FOR BLOOMS & SLABS

Fig. 16—Lanarkshire Works. Layout of 40 in. × 9½ ft. reversing

made in 1901, when a mechanical shearing table was developed at these works. This table anticipated the Ennis shearing table by many years and (apart from the plate-gripping mechanism, which made use of pneumatic cylinders instead of magnets) was almost identical with it. The arrangement of the table is shown in Fig. 11.

36 in. × 10 ft. Reversing Slabbing Mill

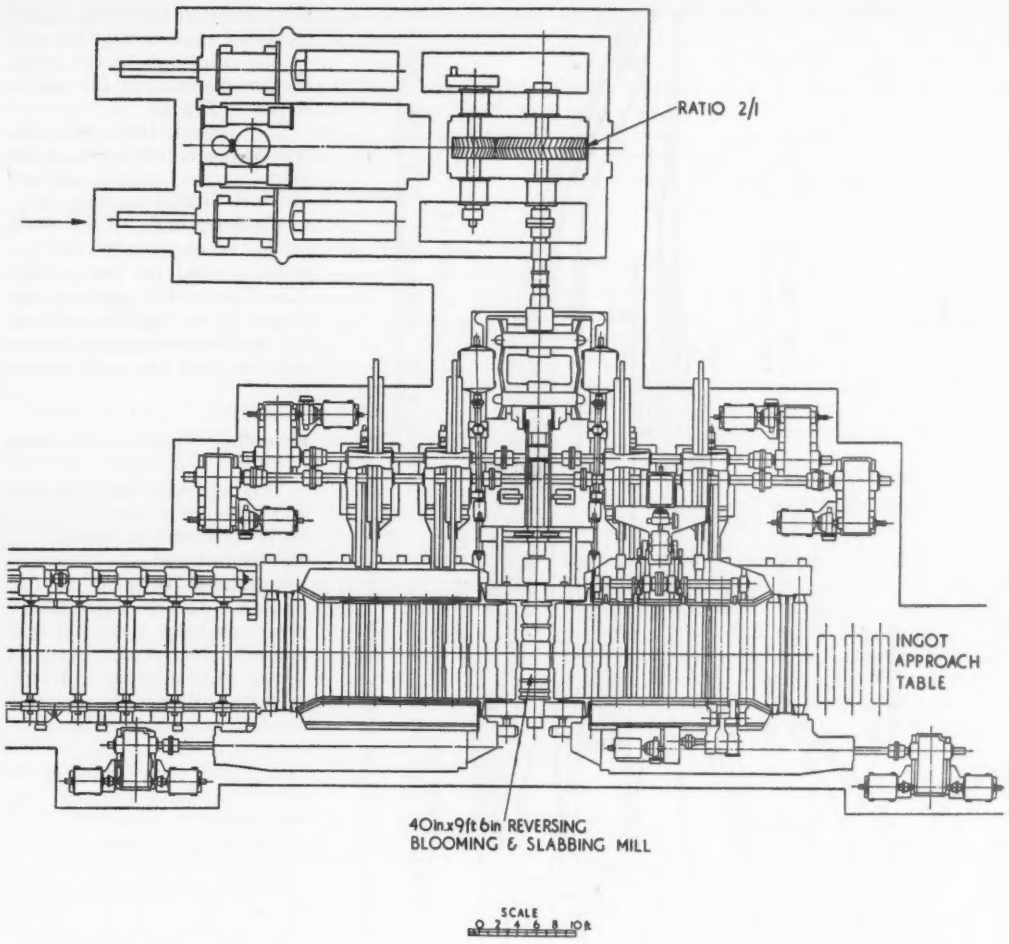
This mill was installed in 1913 and, as far as the sizes of ingots and slabs to be rolled are concerned, its capacity has probably not been exceeded by any mill in the world. It was designed to roll ingots up to 50 tons weight, and is provided with devices for turning and manipulating pieces of this size.

Originally the mill was driven by a pair of horizontal engines, 48 in. dia. × 60 in. stroke, but it was subsequently electrified and partially reconstructed At the present time the rolls are 44 in. dia. × 10 ft. long, and the mill is driven by a reversing electric motor developing a maximum cut-out torque of 300 metre tons at 0–60 r.p.m., with a maximum speed of 120 r.p.m.

The shear, which is of the steam-hydraulic down-cutting type, is capable of cutting slabs up to 66 in. wide × 18 in. thick, and blooms of equivalent cross-section up to 24 in. thick ; this is the largest capacity bloom and slab shear in existence.

CLYDEBRIDGE WORKS

The method of dealing with the ingots from the casting bay to the soaking pits and slabbing mill has



blooming and slabbing mill plant, after partial reconstruction in 1946

been highly developed at these works, resulting in an uninterrupted material flow and minimum fuel consumption. The original plant, installed in 1888, was laid out with the soaking pit and slabbing mill building arranged at right angles to the casting bay and positioned centrally so that the ingots could be transferred from any furnace to the pits with a minimum of movement.

It should be mentioned that the same system of handling the ingots was incorporated in the new plant built in 1917; it has proved highly successful in service.

BLOCHAIRN WORKS

These works are of considerable historic interest, as much special mechanical equipment for use in the manufacture of steel plates was developed here. In addition, a considerable amount of pioneer work in the application of open-hearth steel to shipbuilding and engineering purposes was carried out.

32-in. Reversing Slabbing Mill

The advantages of the early Bessemer steel plants, so far as the casting and subsequent handling of the ingots were concerned, led in 1884 to the application of a system similar to the open-hearth steel plant at these works. At the same time a 32-in. reversing slabbing mill, the first in existence, was installed; the layout of the plant is shown in Fig. 12. This mill, which was driven by a pair of continuously running horizontal engines, 36 in. dia. × 48 in. stroke, fitted with mechanical reversing gear, was equipped with

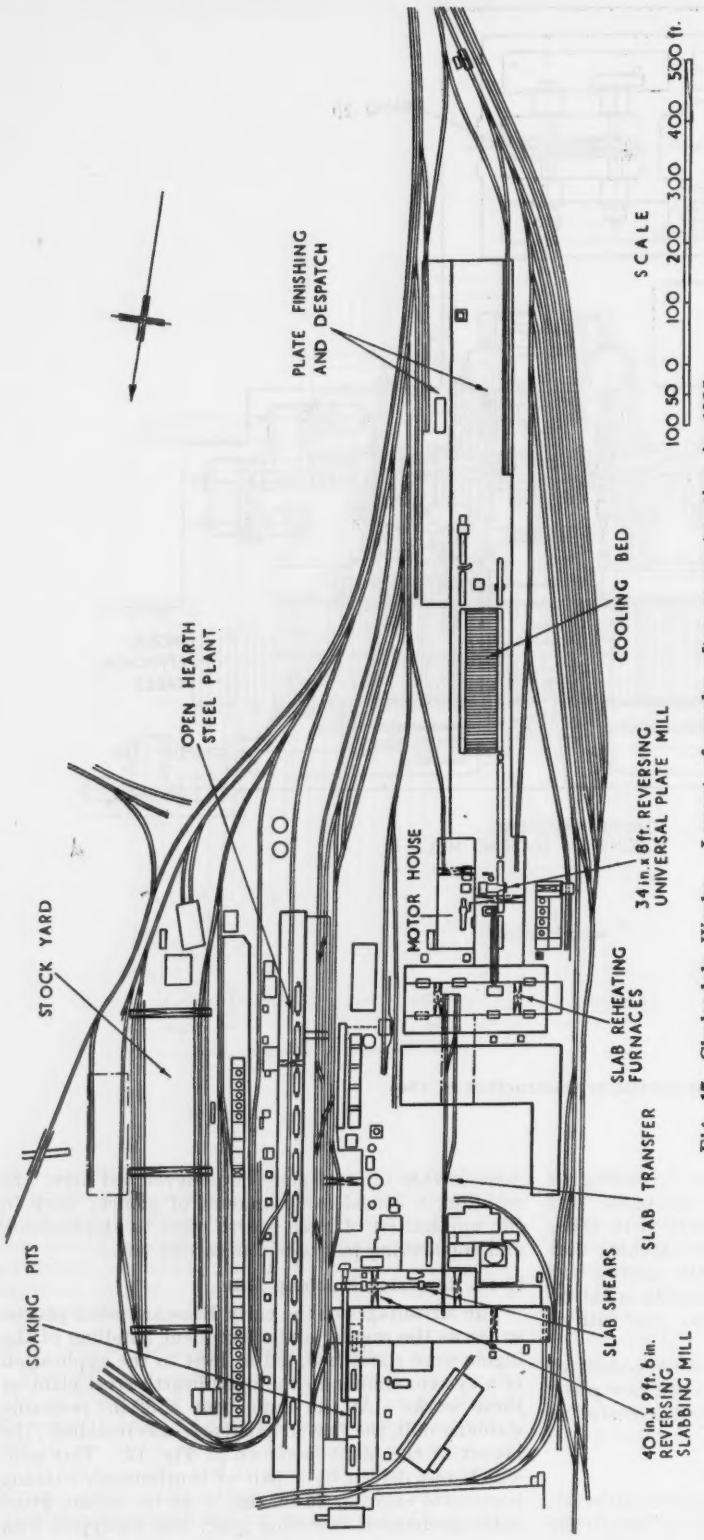


PLATE FINISHING AND DESPATCH
SCALE
100 50 0 100 200 300 400 500 ft.
COOLING BED
OPEN HEARTH STEEL PLANT
34 in. x 8 ft. REVERSING UNIVERSAL PLATE MILL
MOTOR HOUSE
STOCK YARD
SLAB REHEATING FURNACES
SLAB TRANSFER
SOAKING PITS
SLAB SHEARS
40 in. x 9 ft. 6 in. REVERSING SLABBING MILL

Fig. 17—Clydesdale Works. Layout of works after reconstruction in 1925

hydraulically operated ingot-receiving chair and tilting gear on the entry side of the rolls; the arrangement of the mill is shown in Fig. 13.

The period 1885–1895 was one of great activity, and the works at that time comprised an open-hearth melting shop, a slabbing mill, four plate mills, two sheet mills, two bar mills, a plant for the production of locomotive, carriage and wagon tyres, together with all the ancillary equipment necessary for their successful operation.

Reversing Universal Slabbing Mill

This mill was built in 1890 and is the only one of its type to be installed in Britain for slab rolling duty. It is also noteworthy because it dispensed with live roller tables, the piece being moved to and from the rolls on idle rollers, by means of long-stroke hydraulic pushers. The horizontal rolls were 28 in. dia. × 6 ft. 3½ in. long, and one of the vertical rolls, which were located on the delivery side of the mill, was adjustable so that slabs from 30 in. to 60 in. wide could be rolled. All rolls were driven by a pair of horizontal engines, 48 in. dia. × 54 in. stroke, through reduction gearing and a special pinion housing unit. The hydraulically operated slab shear was capable of cutting slabs up to 60 in. wide × 8 in. thick, and was powered by a steam-engine-driven pump. The arrangement of the mill is shown in Fig. 14.

PARKHEAD WORKS

49 in. × 15 ft. Single-Stand Reversing Armour-Plate Mill

This mill was built in 1913 by Davy Brothers, Ltd., Sheffield, and was laid down to deal with armour plates up to a maximum weight of 100 tons each.

The main rolls, which were hollow forgings of nickel steel, were 49 in. dia. × 15 ft. long, and were driven by a pair of horizontal reversing engines,

42 in. dia. × 60 in. stroke, through double reduction gearing and pinions; the lift of the top roll was 45 in.

The ingots were first reduced in thickness and cut to length under a 12,000-ton forging press, and the slabs were reheated in gas-fired movable-hearth furnaces for finish-rolling in this mill.

GLENGARNOCK WORKS

26 in. × 7½ ft. Reversing Plate Mill

This mill was built in 1885 by Miller and Co., Coatbridge, and is typical of many of the earlier plate rolling units; the arrangement of the mill is shown in Fig. 15. It consisted of roughing and finishing stands with rolls 26 in. dia. × 7½ ft. long, and was driven by a pair of horizontal engines, 42 in. dia. × 60 in. stroke.

When the plant was first installed, this engine also drove the 36 in. × 7½ ft. cogging mill, but in 1889 another engine of the same size was added to serve the plate mill only.

LANARKSHIRE WORKS

40 in. × 9½ ft. Reversing Blooming and Slabbing Mill

This mill was built in 1898 by Lamberton and Co., Coatbridge, and was driven at first by a pair of horizontal engines, 46 in. dia. × 60 in. stroke; these were adapted for high-pressure working in 1938, and the cylinders were altered to 38 in. diameter.

At the present time the heavy mill plant at these works is undergoing extensive reconstruction, and, as part of the scheme, the working roller tables and manipulators of the blooming and slabbing mill, together with the shearing equipment, have already been replaced; Fig. 16 shows the layout of the mill as it now exists.

The steam engine driving the mill is being superseded by a direct-coupled electric motor, and following this change the mill train will be replaced; at the same time the rolls will be increased to 43 in. diameter.

HALLSIDE WORKS

In addition to being the first works in Scotland to produce steel by the open-hearth process, the Hallside Works were for many years the most important. At the end of 1879 it was intended to increase their productive capacity by the installation of a considerable amount of additional equipment, including four plate mills, but the Blochairn Works were acquired about this time and the scheme was not developed to fruition.

The plant as it existed in 1880 comprised open-hearth steel melting shop, cogging and forge hammers, and rail, plate, bar, and guide mills.

26-in. Reversing Combination Section and Plate Mill

This mill was intended primarily for the production of rails and heavy sections, and was of the 2-stand reversing type with 26-in. dia. rolls. It was also capable of rolling plates, and in this respect anticipated some of the more recent combination section and plate mills. Of further historical significance is the fact that it was driven by one of the first twin tandem

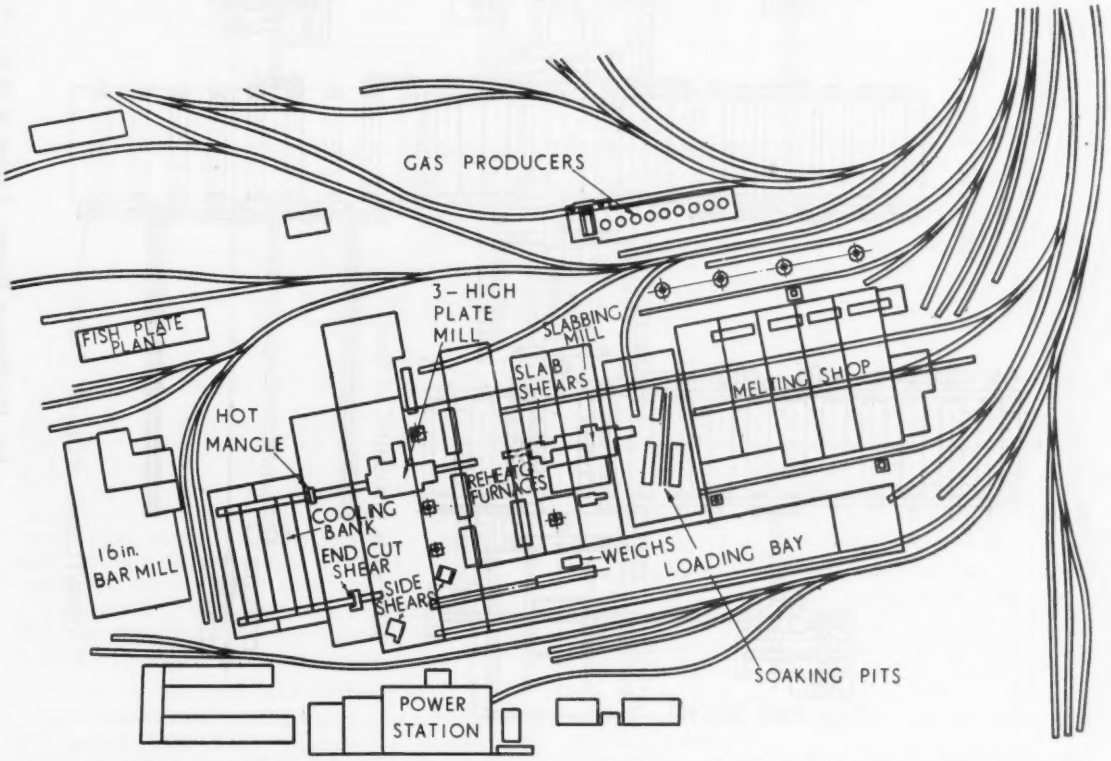


Fig. 18—Mossend Works. Layout of works, showing plate mill plant. (Scale, 1 in. = 160 ft.)

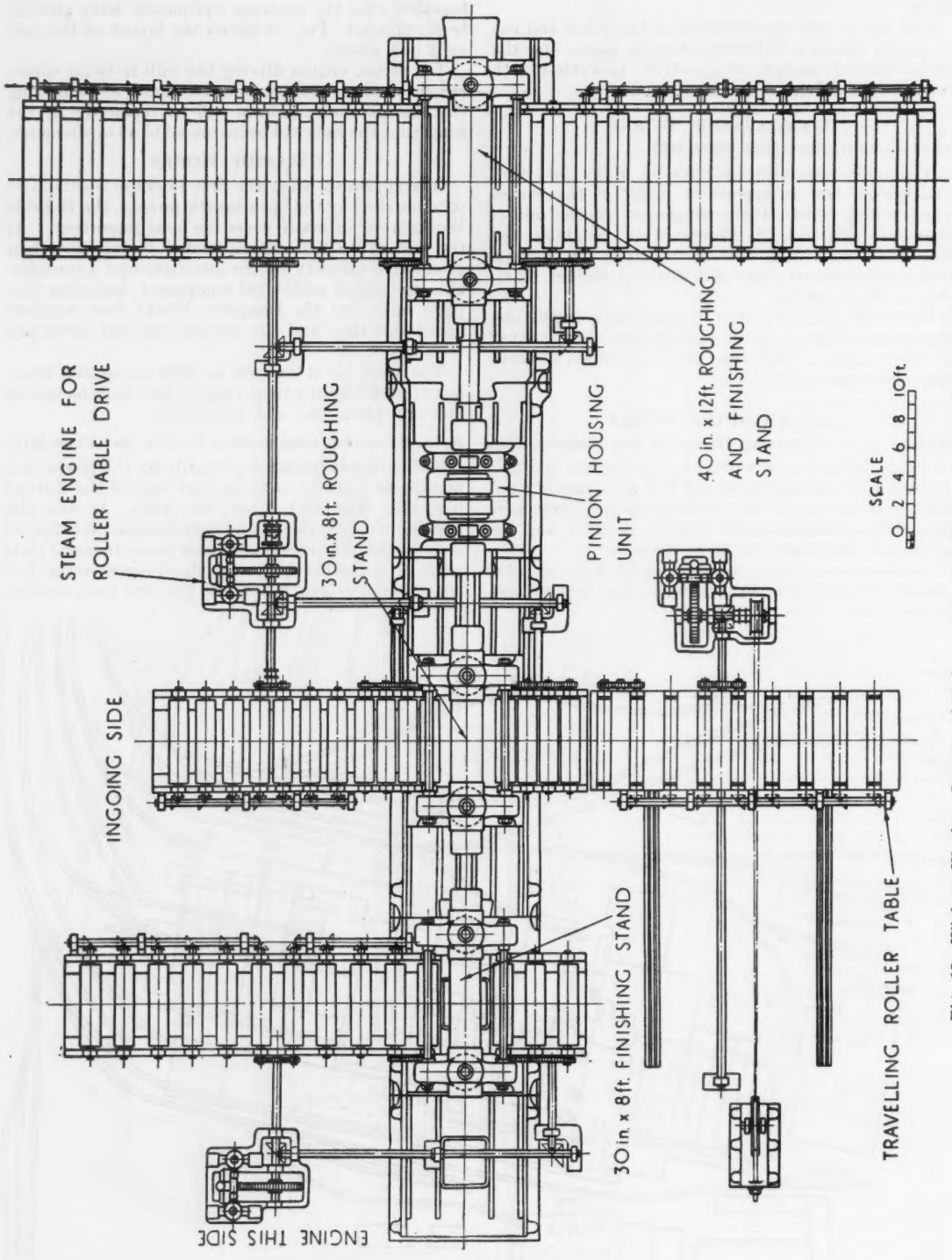

STEAM ENGINE FOR ROLLER TABLE DRIVE
30 in. x 8ft. ROUGHING STAND
PINION HOUSING UNIT
40 in. x 12ft. ROUGHING AND FINISHING STAND
SCALE 0 2 4 6 8 10ft.
INGOING SIDE
30 in. x 8ft. FINISHING STAND
TRAVELLING ROLLER TABLE
ENGINE THIS SIDE

Fig. 19—Wishaw Works. Layout of 30 in. × 8 ft. and 40 in. × 12 ft. reversing plate mills

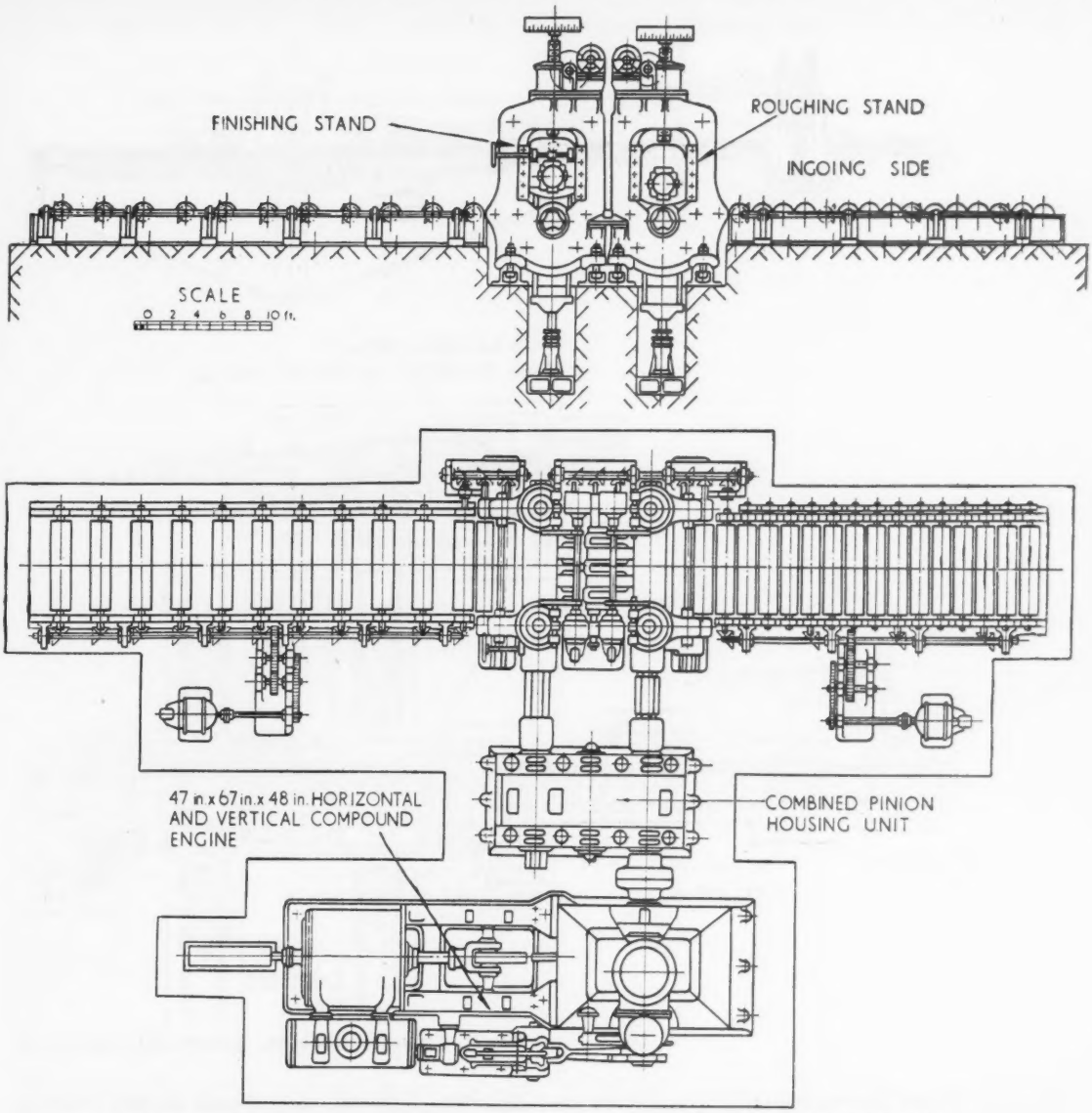

FINISHING STAND
ROUGHING STAND
INGOING SIDE
SCALE
0 2 4 6 8 10 ft.
47 in x 67 in x 48 in. HORIZONTAL AND VERTICAL COMPOUND ENGINE
COMBINED PINION HOUSING UNIT

Fig. 20—Wishaw Works. Arrangement of 30 in. × 6½ ft. tandem reversing plate mill

compound reversing engines to be built for mill duty. This engine, which was supplied in 1878 by Miller and Co., Coatbridge, had cylinders 30 in. and 50 in. dia. × 60 in. stroke, and worked with steam at a pressure of 120 lb./sq. in. Besides being direct-coupled the engine was also geared to the mill, so that the rolls could be run at a lower speed than the engine when dealing with plates.

Unfortunately this engine, which weighed more than 300 tons, was not too successful, and it was ultimately rebuilt as a simple high-pressure unit.

CLYDESDALE WORKS

These works were extensively reconstructed during the period 1922–1925, to meet the demand for universal and sheared plates. The existing slabbing mill was enlarged and new heating equipment installed, and the finishing mills were superseded by a 34 in. × 8 ft. single-stand reversing universal plate mill with a complete range of ancillary equipment; the layout of the works after reconstruction is shown in Fig. 17.

34 in. × 8 ft. Reversing Universal Plate Mill

This mill was laid down primarily for the rolling of universal plates in widths up to 48 in., but it was also capable of producing sheared plates up to 7 ft. wide × 1½ in. thick. The horizontal rolls were 34 in. dia. × 8 ft. long and the vertical rolls, two on each of the entry and delivery sides of the mill, were 26⅝ in. diameter.

The slabs were reheated in five 'in-and-out' hearth

Fig. 19—Wishaw Works. Layout of 30 in. × 8 ft. and 40 in. × 12 ft. reversing plate mills

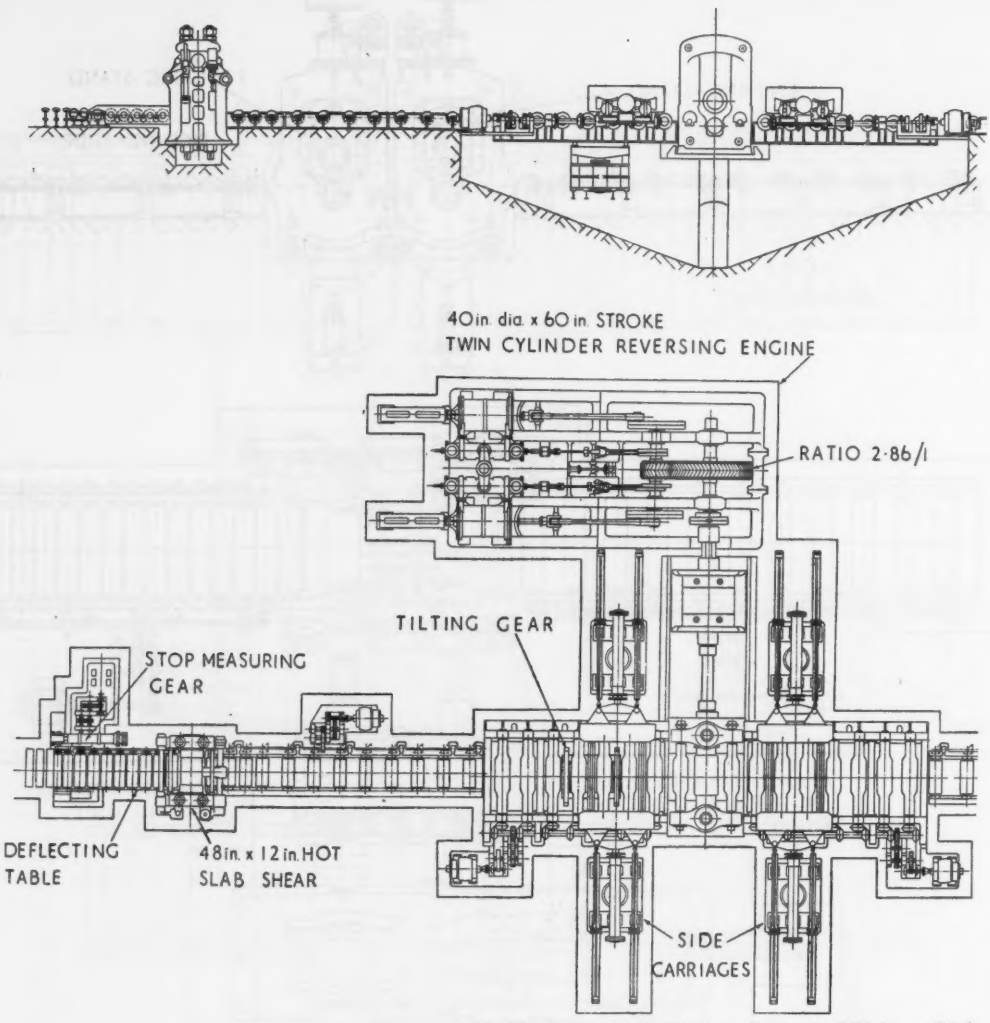


Fig. 21—Calderbank Works. Layout of 34 in. × 7½ ft.

type regenerative furnaces fired with raw producer gas and served by overhead charging machines. The heated slabs were conveyed to the mill by a travelling carriage from which they were transferred sideways on to the working roller table by means of an electrically operated pusher. The finishing equipment comprised a hot mangle in tandem with the mill delivery roller table, a plate-straightening device for universal plates, chain carry-over type cooling banks, rotary and guillotine shears, and piling arrangements.

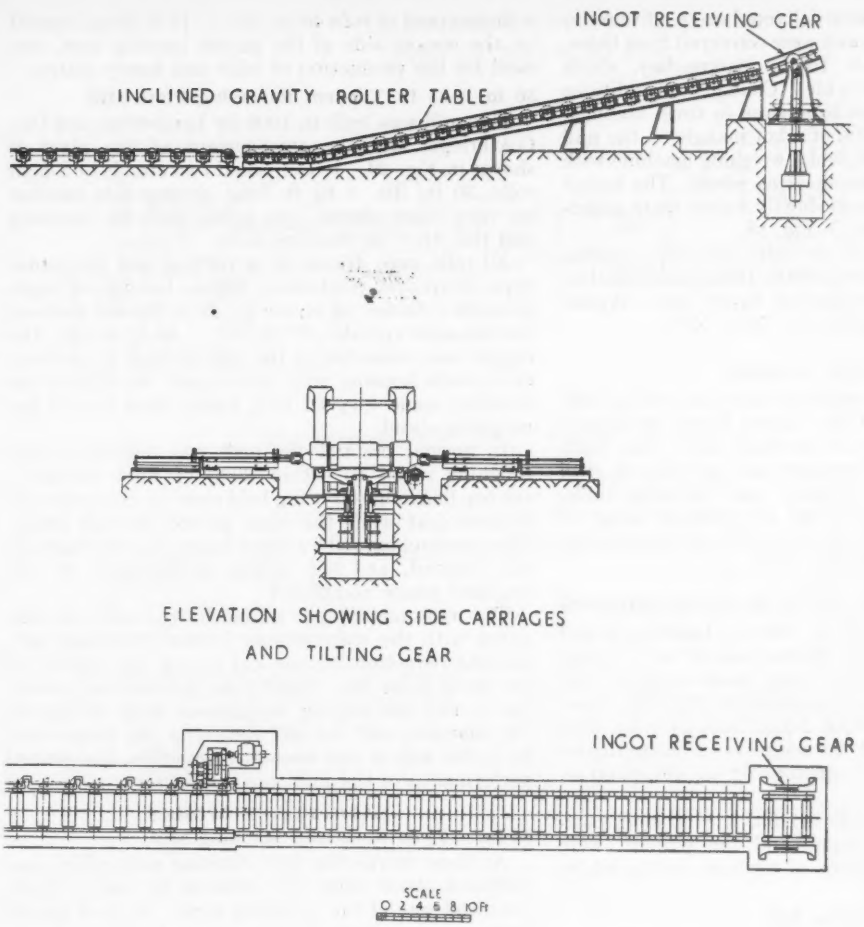
The mill was driven by a direct-coupled electric motor capable of developing a maximum torque of 180 metre tons up to 80 r.p.m. and of attaining a maximum speed of 135 r.p.m. by field weakening.

MOSSEND WORKS

29½ in. × 21½ in. × 7 ft. 8½ in. Three-High Plate Mill

This mill was built in 1908 and marked an important departure from the conventional 2-stand reversing mill which had predominated up to that time. It was also noteworthy for two other reasons: (i) by virtue of its prime mover, which was a direct-coupled slow-speed gas engine, and (ii) it was the first plate mill in Scotland to be equipped with a fully mechanized cooling and inspection bank.

The gas engine was chosen following the successful application of a similar unit at the Parkhead Works of the same Company, where a pull-over type light plate and sheet mill was driven in this way. In both cases the engines were of the Oechellhaueser type, the one for the Mossend mill having a single cylinder $43\frac{5}{16}$ in. dia. × $53\frac{1}{8}$ in. stroke and developing 1850 h.p. when running at its normal speed of 75 r.p.m.; a flywheel with a stored energy of 33,600 h.p.sec. was mounted on the engine crankshaft. Clean gas was supplied from a Mond producer plant which also fed



reversing slabbing mill plant, reconstructed 1915

the soaking pits and slab reheating furnaces. Because of its relatively high upkeep and operating costs, the engine was replaced in 1918 by a 2000-h.p. motor running at 300/270 r.p.m., which was coupled to the mill through single reduction gearing, the flywheel being retained.

The mill was equipped with electrically operated and hydraulically balanced tilting tables back and front of the rolls, their motion being synchronized with that of the middle roll, which was raised and lowered hydraulically. The table rollers were electrically driven through an arrangement of connecting rods and cranks, but this system of driving, which was intended to overcome some of the difficulties experienced at that time with mitre gearing, was not a success.

The finished plates were conveyed by live roller tables to a point abreast of the cooling bank, where they were turned over for surface inspection, and then transferred from the rollers to the bank. This was about 100 ft. long × 100 ft. wide, and consisted of rails supported approximately 4 ft. apart on brackets, with ample space below for free circulation of cooling air. The plates were moved across the bank by power-operated skids, and were delivered, after cooling and marking, on to another live roller table; this carried the plates to a cross-cut shear, with a capacity of 8 ft. wide × 1 in. thick, which cropped and cut the plates to length as required.

The plates were cut to width on two shears, located approximately 60 ft. and 110 ft. respectively beyond the cross-cut shear and about 30 ft. to each side of it. These side shears had a blade length of 11 ft. and a gap of 2 ft. 7½ in., and each was fitted with small auxiliary blades at the rear for cutting the scrap into charging box sizes. The floor area around the shears was laid out with castors, to minimize manual effort during shearing.

The sheared plates were delivered on to a live roller table serving a mangle, and were conveyed from there, also by live roller table, to the loading bay, which was 210 ft. long × 60 ft. wide. Changes and additions were made to the plant from time to time, amongst these being the provision of a hot mangle on the mill side of the cooling bank, and a weighing machine with roller tables beyond the shearing plant. The layout of the works, as it existed shortly before plate manufacture ceased, is shown in Fig. 18.

The chief product of the mill was ships' plates, and the average output was 1600–1800 tons of finished material per week ; production figures for a typical week's operation are given in Table XIV.

WISHAW WORKS

These works were extensively reconstructed in 1893 under the direction of Mr. James Riley, previously of The Steel Company of Scotland, Ltd. The main equipment comprised Bessemer and open-hearth steel melting shops, bar, cogging, and finishing mills, slabbing mill, plate mills and an extensive range of ancillary machinery ; a tandem mill for the production of light plates was added in 1906.

30 in. × 8 ft. and 40 in. × 12 ft. Reversing Plate Mills

These mills were built in 1893 by Lamberton and Co., Coatbridge, for the production of boiler, ship, and merchant plates in a wide range of sizes ; the arrangement of the mills is shown in Fig. 19. They comprised three stands of 2-high rolls in train with one pinion housing unit, the complete mill being driven by a pair of horizontal engines 52 in. dia. × 60 in. stroke.

Two stands of rolls, 30 in. dia. × 8 ft. long, positioned between the engine and the pinions, were provided for rolling plates of medium width, whilst a single stand of rolls 40 in. dia. × 12 ft. long, located on the remote side of the pinion housing unit, was used for the production of wide and heavy plates.

30 in. × 6½ ft. Tandem Reversing Plate Mill

This mill was built in 1906 by Lamberton and Co., Coatbridge, and the arrangement of the plant is shown in Fig. 20. It comprised two stands of 2-high rolls, 30 in. dia. × 6½ ft. long, arranged in tandem on very close centres, one being used for roughing and the other for finishing duty.

All rolls were driven by a vertical and horizontal type compound condensing engine having one high-pressure cylinder, 42 in. dia. × 48 in. stroke, and one low-pressure cylinder, 67 in. dia. × 48 in. stroke ; the engine was connected to the mill through a combination pinion housing unit, which gave the rolls of the finishing stand a speed 15% higher than that of the roughing stand.

In normal practice the slab was reduced in the roughing stand to within 20% of final thickness, the top finishing roll being held clear by the hydraulic balance gear while the piece passed through freely. The top roughing roll was then raised, the top finishing roll lowered, and the rolling of the plate to the required gauge completed.

The main advantage claimed for this mill, as compared with the conventional 2-stand reversing mill, was the reduction in time lost during the transfer of the piece from the roughing to the finishing stand, but it also had certain weaknesses, such as difficult roll changing and the fact that only one piece could be in the mill at any time ; nevertheless, the general performance of the mill was satisfactory.

Table XIV

MOSSEND WORKS : TYPICAL PRODUCTION FIGURES FOR 29½ in. × 21½ in. × 7 ft. 8½ in. THREE-HIGH PLATE MILL

Week ending 11.8.28.

Date	Charged Weight	No. of Slabs	Average Slab Weight
	Tons cwt. qr.		cwt. qr.
5.8.28	167 13 0	103	33 2
6.8.28	106 13 2	87	24 2
	144 12 2	103	28 0
	122 16 3	100	24 2
7.8.28	131 5 3	93	28 1
	139 0 1	97	28 2
	99 1 1	96	20 2
8.8.28	145 0 3	84	34 2
	85 12 2	95	18 0
	141 16 3	85	33 1
9.8.28	85 13 2	99	17 1
	145 7 1	118	24 2
	90 19 3	80	22 2
10.8.28	122 5 0	112	21 3
	124 3 2	88	28 1
	111 1 2	100	22 0
11.8.28	111 19 2	53	42 1
Total	2075 3 0	1593	26 0

CALDERBANK WORKS

34 in. × 7½ ft. Reversing Slabbing Mill

At these works the first slabbing mill, which was installed about 1890, had rolls 40 in. dia. × 7½ ft. long and was of the reversing type. It is of special interest as, similarly to the universal mill which was built about the same time at the Blochairn Works, it was equipped with dead roller tables and made use of long-stroke hydraulic pushers for moving the piece to and from the rolls. In 1915 it was extensively reconstructed, and the roll diameter was reduced to 34 in. ; the layout of the plant at that date is shown in Fig. 21.

The mill was driven by a pair of horizontal engines, 40 in. dia. × 60 in. stroke, and was fitted with hydraulically operated side carriages back and front of the rolls, and tilting gear on the delivery side only. The ingots, of a maximum weight of 7 tons, were brought to the rolls by way of a receiving gear and an inclined gravity roller table which fed the pieces on to the driven approach table.

28 in. × 19 in. × 7 ft. Three-High Plate Mill

This mill was built in 1910 by Lamberton and Co., Coatbridge, and was unique in having as prime mover a Parsons mixed-pressure turbine, operating on exhaust steam from the slabbing and heavy plate mills and/or live steam. The turbine was designed to develop 750 b.h.p. at 2000 r.p.m., and was coupled to the mill through double reduction gearing to give a mill speed of 70 r.p.m. ; a cast-iron 23-ft. dia. flywheel, weighing, with its shaft, about 100 tons,

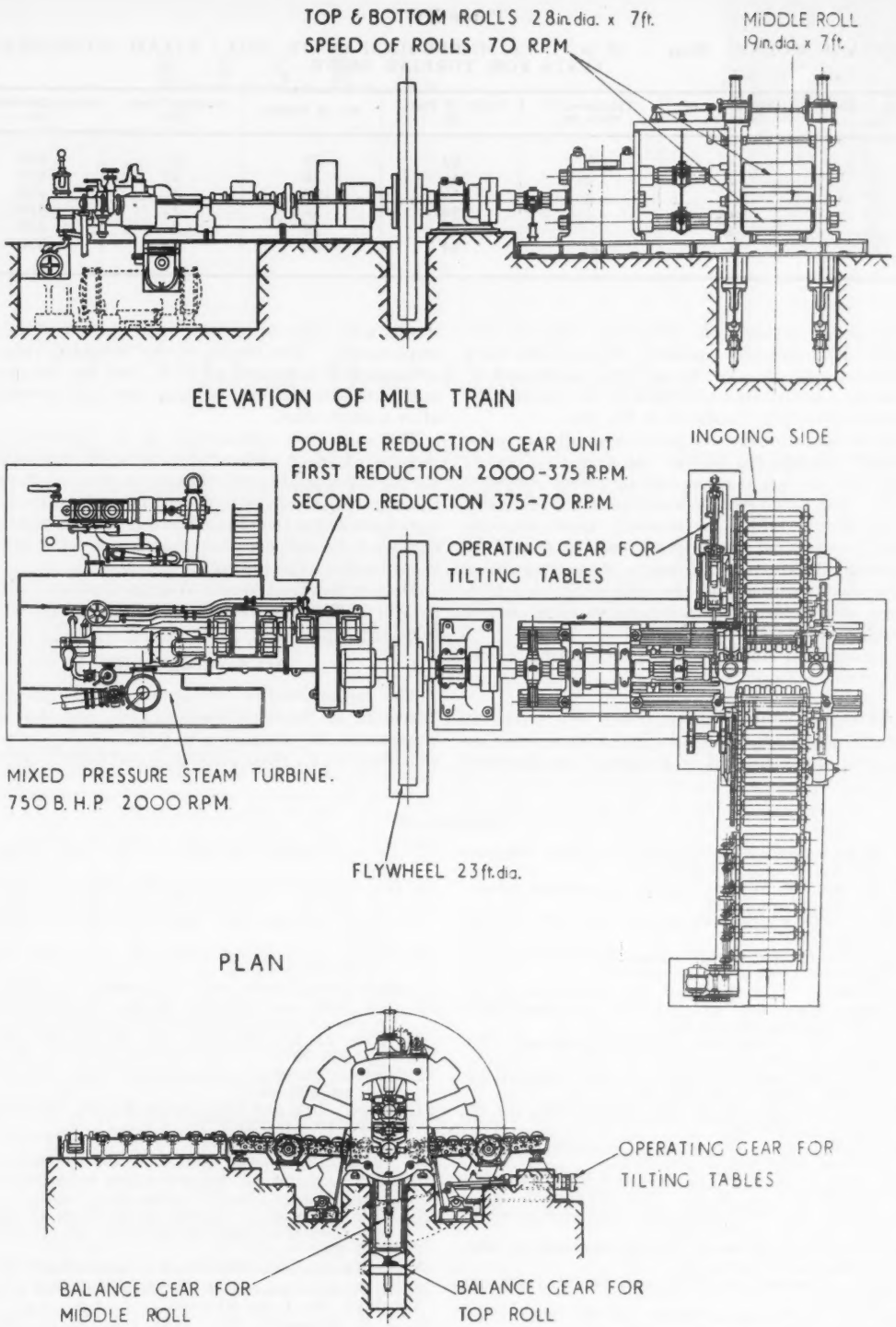


Fig. 22—Calderbank Works. Arrangement of 28 in. × 19 in. × 7 ft. three-high plate mill. (Scale, $\frac{1}{16}$ in. = 1 ft.)

Table XV

CALDERBANK WORKS : 28 in. × 19 in. × 7 ft. THREE-HIGH PLATE MILL : STEAM CONSUMPTION TESTS FOR TURBINE DRIVE

Weight of Slab, cwt.	Thickness of Slab, in.	Thickness of Plate, in.	Width of Plate, in.	No. of Passes	Rolling Time, min.	Steam Consumed, lb.
8	4	$\frac{3}{16}$	62	28	2	490
21	5	$\frac{1}{4}$	46	30	$2\frac{3}{4}$	800
15	5	$\frac{5}{16}$	58	29	3	450
12	4	$\frac{1}{4}$	58	28	$2\frac{1}{2}$	420
26	6	$\frac{21}{40}$	72	28	2	400
24	6	$\frac{21}{40}$	44	30	$3\frac{1}{4}$	520

was interposed between the reduction gear set and the mill. Hydraulically operated tilting tables were provided on both sides of the mill, the movement of these being synchronized with that of the middle roll. The layout of the plant is shown in Fig. 22.

From an operational standpoint this mill was quite successful, although the turbine was somewhat underpowered and the fall in speed on long pieces was very marked. Also much trouble was experienced initially with the tilting tables, particularly those sections adjacent to the rolls, as the gears were inadequately protected and lubricated. However, these weaknesses were largely overcome and the mill attained a high standard of performance, in regard to both output and quality of product.

Information on steam consumption during a test run is given in Table XV.

36-in. Reversing Plate Mill

This mill was built in 1890 by Lamberton and Co., Coatbridge, and consisted of roughing and finishing stands with rolls 36 in. dia. × 10 ft. and 8½ ft. long respectively. The length of the roughing rolls was subsequently increased to 12 ft., but the change was not a success and the original size was reverted to after a short time.

The mill was noteworthy as it operated for a number of years with a novel form of friction drive for the top roughing roll. Owing to pinion failure and the non-availability of replacement parts, plain blanks were installed in the pinion housing, and by tightening the cap bolts sufficient adhesion was created between them to drive the top roll.

During the First World War the mill was adapted to roll shell bars, but the tonnage produced was relatively small.

Acknowledgments

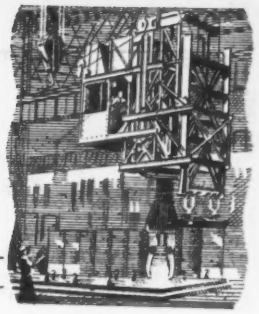
The author wishes to express his thanks to the Directors of Messrs. Colvilles, Ltd., and Associated Companies, for permission to publish this paper ; and to colleagues for their assistance and helpful criticism.

References

1. J. Riley : *Journal of The Iron and Steel Institute*, 1885, No. II, pp. 394–409.
2. H. Bumby, W. Wylie, and H. Archibald : *Ibid.*, 1901, No. II, pp. 9–28.
3. Anon. : *The Engineering Review*, 1911–12, vol. 25, pp. 133–135.
4. J. Riley : *Proceedings of the Institution of Mechanical Engineers*, 1895, July, pp. 436–461.
5. R. Meade : " The Coal and Iron Industries of the United Kingdom," pp. 744–747. London, 1882 : Crosby Lockwood and Co.
6. Anon. : *The Engineering Review Supplement*, 1894, vol. II, Dec. 20, pp. 5–9.
7. Anon. : *The Engineer*, 1923, vol. 136 ; Aug. 31, pp. 218–220 ; Sept. 7, pp. 245–248.
8. Anon. : *Iron and Coal Trades Review*, 1901, vol. 63, Sept. 6, pp. 559–562.
9. A. Lamberton : *Journal of The Iron and Steel Institute*, 1908, vol. I, pp. 30–53.
10. St. John V. Day : " The Iron and Steel Industries of Scotland," pp. 49–59. 1876, Edinburgh.
11. J. Riley : *Journal of The Iron and Steel Institute*, 1884, No. II, pp. 443–452.
12. Anon. : *The Engineering Review Supplement*, 1895, No. II, Jan. 21, pp. 4, 5.
13. Anon. : *Engineering*, 1913, vol. 95, May 30, pp. 740–742.
14. Anon. : *The Engineer*, 1896, vol. 81 ; Feb. 7, pp. 130–131 ; Feb. 14, pp. 153–155.
15. Anon. : *Iron and Coal Trades Review*, 1899, vol. 58, Feb. 10, pp. 239–242.
16. Anon. : *Journal of The Iron and Steel Institute*, 1885, No. II, pp. 522–524.
17. Anon. : *Engineering*, 1879, vol. 27, Apr. 4, pp. 274, 275.
18. *Ibid.*, vol. 28, Dec. 12, pp. 449, 450.
19. J. S. Jeans : " Steel, its History, Manufacture and Uses," pp. 482–485. London, 1880 : E. and F. N. Spon.
20. Anon. : *Engineering*, 1925, vol. 120 ; July 10, pp. 36–38 ; July 24, p. 93.
21. *Ibid.*, 1908, vol. 86 ; Nov. 13, p. 666 ; Nov. 27, p. 708.
22. *Ibid.*, 1922, vol. 114 ; Oct. 13, pp. 447, 448 ; Oct. 20, p. 484 ; Nov. 3, pp. 543–545 ; Nov. 17, pp. 603–606 ; Nov. 24, pp. 641–643 ; Dec. 8, p. 704 ; Dec. 29, pp. 795–797.
23. Anon. : *The Engineering Review*, 1894, vol. II, Nov. 20, pp. 153–157.
24. Anon. : *Iron and Coal Trades Review*, 1897, vol. 55, Nov. 19, pp. 733–777.
25. *Ibid.*, 1910, vol. 80, Mar. 4, pp. 324, 325.
26. Anon. : *Engineering*, 1895, vol. 59 ; Apr. 5, pp. 427–429 ; Apr. 26, pp. 535–539 ; May 17, pp. 623, 624 ; June 14, pp. 755–757 ; June 28, p. 822.
27. A. Q. Carnegie : *Journal of the West of Scotland Iron and Steel Institute*, 1911, vol. 18, pp. 193–204, 217–232.
28. J. Riley : *Ibid.*, 1892–94, vol. 1, pp. 93–98, 103–106.
29. J. Riley : *Journal of The Iron and Steel Institute*, 1887, No. I, pp. 211–162.
30. J. M. Borland : *Ibid.*, 1947, vol. 155, pp. 593–597.
31. F. Siemens : *Ibid.*, 1884, No. II, pp. 434–442.
32. A. Lamberton : *Journal of the West of Scotland Iron and Steel Institute*, 1894–96, vol. 2, pp. 143–147, 166–174.

B. I. S. R. A.

BRITISH IRON AND STEEL RESEARCH ASSOCIATION



Ingot Heat Conservation

SOME METHODS OF CALCULATING INTERNAL TEMPERATURES FROM SURFACE TEMPERATURES OF INGOTS

SYNOPSIS

Methods are given for the calculation of the internal temperatures of ingots (*a*) by the use of the theoretical equation for a solid with known and constant thermal properties and initially at a uniform temperature, which is heating or cooling in surroundings at constant temperature; (*b*) by surface temperature measurements when the thermal properties are unknown but are assumed constant (this method is derived from the theoretical equation, and is subject to the same limitations); and (*c*) by an empirical equation using measured surface temperatures.

Introduction

It is seldom possible to measure directly the internal temperature of steel ingots in the various cooling and heating stages between teeming and rolling. A knowledge of such temperatures would, however, be of considerable assistance in keeping the duration of each stage to the minimum, for the purpose of obtaining maximum fuel economy and smooth regular operation of the mill.

Theoretical equations have been derived, giving the temperature distribution in solids of simple geometrical shape and having uniform thermal properties, for a number of conditions of heating or cooling. The most recent comprehensive and authoritative work on this subject is that of Carslaw and Jaeger.[1] The main industrial application of these equations is to provide a reasonable estimate of the time required to obtain some desired temperature distribution, or alternatively of the temperature distribution at some given time, in the absence of experimental data.

Methods by which the temperature distribution can be calculated from surface temperature measurements have been put forward and assessed by members of the staff of the Plant Engineering Division and the Physics Department of the British Iron and Steel Research Association. The theoretical equation considered is specifically for a rectangular ingot, initially at a uniform temperature, heating or cooling with surroundings at a constant temperature; its use is described in the first part of the paper.

The second part describes methods derived from the theoretical equations used when the thermal constants are unknown but surface temperatures can be measured, and was contributed by L. H. W. Savage with a nomogram constructed by J. Stringer. The third part puts forward an empirical graphical method based on surface temperatures, and was contributed by A. V. Brancker; this has been assessed, by L. F. Daws and H. Herne, within the limitations of the theoretical method given below.

It must be emphasized that the assumptions involved are such that there are certain to be differences between actual and calculated temperatures, and these differences can only be assessed by experiment.

THEORETICAL TEMPERATURE DISTRIBUTION IN RECTANGULAR INGOTS

It is necessary to make the following assumptions:

(1) The ingot is a rectangular parallelepiped
(2) The ingot is initially at a uniform temperature
(3) The thermal properties (conductivity, specific heat, and diffusivity) of the ingot are constant
(4) The surroundings are at a constant temperature throughout the heating or cooling period
(5) The heat transfer coefficient between the ingot and the surroundings is constant
(6) There are no latent heats.

As examples showing the drastic nature of these assumptions, Fig. 1*a* gives a typical curve for the thermal conductivity of mild steel (0·23% carbon) *versus* temperature, and Fig. 1*b* gives a correspond-

Paper No. PE/A/45/49 of the Fuel Research Committee of the Plant Engineering Division of the British Iron and Steel Research Association, received 2nd March, 1950.

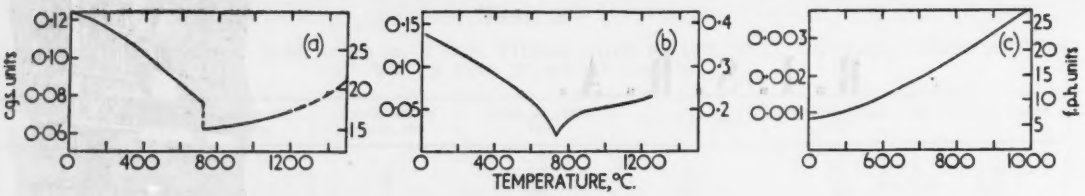


Fig. 1—Variation of thermal properties of mild steel (0·23% C) with temperature. (*a*) Thermal conductivity, (*b*) thermal diffusivity, (*c*) heat transfer coefficient (combined radiation and natural convection from vertical surfaces to cold surroundings)

ing curve for the thermal diffusivity (*i.e.*, ratio of conductivity to specific heat per unit volume). In Fig. 1*c* is shown the variation in the heat transfer coefficient (heat flux per unit area per unit time per degree temperature difference between surface and surroundings) caused by black body radiation and natural convection, for a free vertical surface between 400° and 1000° C., with surroundings at 0° C.

With these assumptions, the temperature at any point in an ingot is obtained by means of a complicated mathematical series (*see* Appendix). The value of this series has been computed for a wide range of variables by Russell,[2] whose published tables have been used in these calculations. Other graphs for the same purpose have also been published.[3]

Method

Let $2a$, $2b$, $2c$ = dimensions of ingot
K = thermal conductivity of ingot
D = thermal diffusivity of ingot
h = heat transfer coefficient
t = time at which temperature is required
θ' = initial uniform temperature of ingot
θ'' = constant temperature of surroundings.

The temperature θ at any point (x, y, z) in the ingot (*see* Fig. 2) is obtained from the functions H, T, and U given in the Russell tables, by the following steps :

(1) Calculate $H_x = ha/K$; $T_x = Dt/a^2$; and x/a. Reference to the appropriate table for H, interpolating if necessary, gives a value U_x.

(2) Calculate $H_y = hb/K$; $T_y = Dt/b^2$; and y/b. Reference to the tables gives a second value, U_y.

(3) Calculate $H_z = hc/K$; $T_z = Dt/c^2$; and z/c. Reference to the tables gives a third value, U_z.

(4) The required temperature is then obtained from the equation

$$\theta = (\theta' - \theta'')U_x.U_y.U_z + \theta''.$$

METHODS USING SURFACE TEMPERATURE MEASUREMENTS

The theoretical approach is rigorously true only if the thermal conductivity, diffusivity, and surface heat transfer coefficient are constant during the heating or cooling period. It is possible, however, that even when these properties vary with temperature, as with steel ingots, the use of mean values will give results of sufficient accuracy for many industrial purposes.

When the properties vary considerably, as shown in Figs. 1*a–c*, it is not clear how mean values should be selected. Another difficulty is that for some materials little or no data may be available. However, if the surface temperatures can be measured, the internal temperatures at the time of measurement can be calculated on the assumption that there is some mean, but unknown, value of each property. The assumptions stated on p. 71 must also be accepted.

Methods

The temperatures referred to are relative to the surroundings ; *i.e.*, if the temperature of the surroundings is not zero, it must be subtracted from the true surface temperatures before proceeding with the calculation, and subsequently must be added to the answer to give the true centre temperature.

The centre temperature can be calculated, from temperatures measured at points shown in Fig. 2, as follows :

(1) From the product of the two mid-face temperatures (M, N) divided by the temperature of the mid-plane corner (P)

(2) From the square root of the product of the

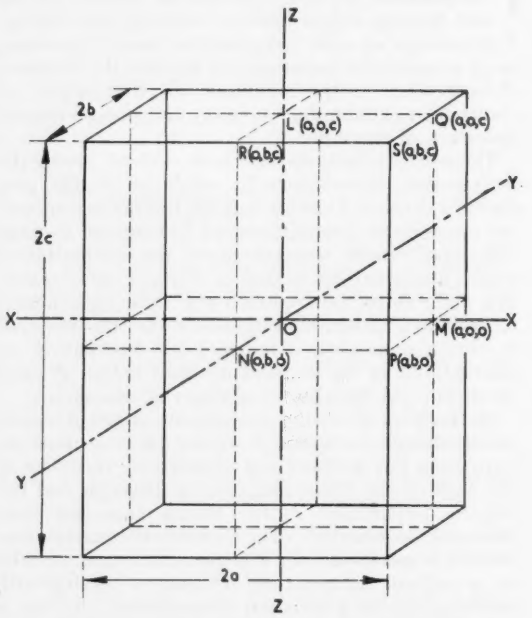


Fig. 2—Dimensional representation of ingot, showing points at which surface temperatures were measured

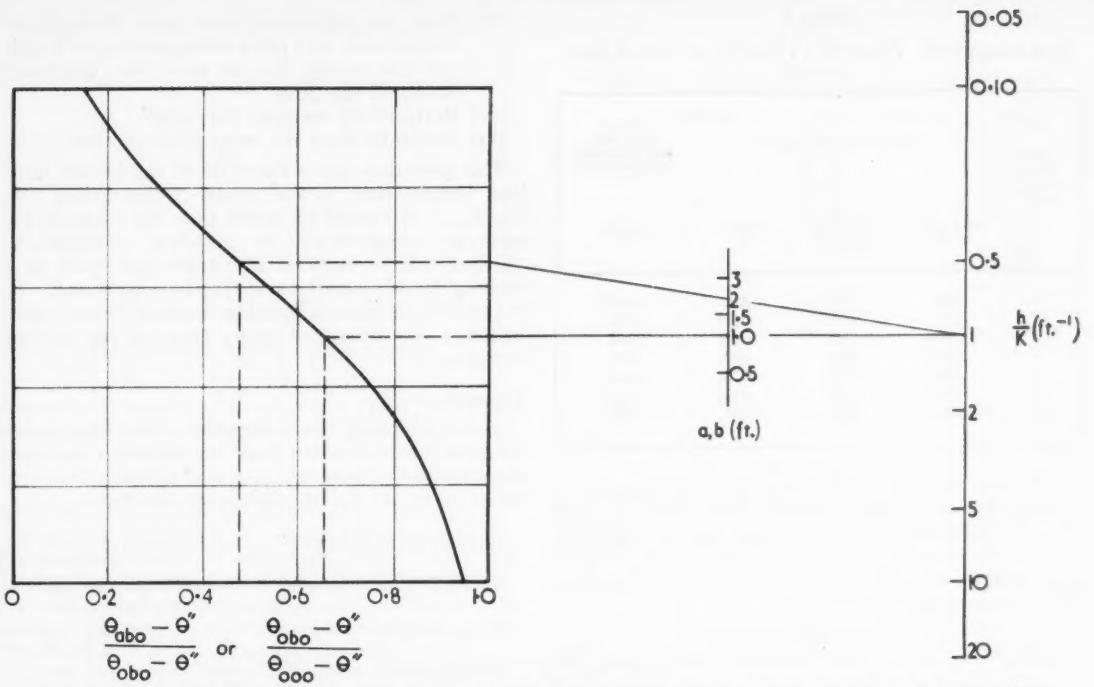


Fig. 3—Nomogram for the determination of centre temperature of ingot from mid-face and mid-edge temperatures. (θ'' = constant temperature of surroundings)

three mid-face temperatures (L, M, N) divided by the corner temperature (S)

(3) From the product of the three mid-edge temperatures (P, Q, R) divided by the square of the corner temperature (S)

(4) From the ratio mid-edge temperature (P)/mid-face temperature (N), by means of a nomogram (Fig. 3) which gives the ratio mid-face temperature (N)/centre temperature (O). This method is appropriate if conditions permit measurement on only one mid-plane surface, but it is limited by the length of the heating or cooling period.

Derivation

The temperature at any point (x, y, z) in an ingot of dimensions $2a \times 2b \times 2c$ is obtained from an expression of the form :

$$\theta_{xyz} = \theta'.\mu(x, a, h).\mu(y, b, h).\mu(z, c, h)$$

where $\mu(x, a, h)$, etc., are functions of the variables (*see* Appendix). In particular, the centre temperature is given by :

$$\theta_{ooo} = \theta'.\mu(o, a, h).\mu(o, b, h).\mu(o, c, h)$$

(1) *Two mid-face temperatures and mid-plane corner temperature* (*points M, N, P, Fig.* 2)—The following identities exist :

$$\begin{array}{l}\text{at } M,\ \theta_{aoo} = \theta'.\mu(a, a, h).\mu(o, b, h).\mu(o, c, h)\\ \text{at } N,\ \theta^{obo}_{aoo} = \theta'.\mu(o, a, h).\mu(b, b, h).\mu(o, c, h)\\ \text{at } P,\ \theta^{obo}_{abo} = \theta'.\mu(a, a, h).\mu(b, b, h).\mu(o, c, h)\end{array}$$

$$\text{whence } \frac{\theta_{aoo}.\theta_{obo}}{\theta_{abo}} = \theta'.\mu(o, a, h).\mu(o, b, h).\mu(o, c, h) = \theta_{ooo}$$

(2) *Three mid-face temperatures and common corner temperature* (*points L, M, N, and S, Fig.* 2)—The identities are :

$$\begin{array}{l}\text{at } L.\ \theta_{ooc} = \theta'.\mu(o, a, h).\mu(o, b, h).\mu(c, c, h)\\ \text{at } M,\ \theta^{aoo}_{ooc} = \theta'.\mu(a, a, h).\mu(o, b, h).\mu(o, c, h)\\ \text{at } N,\ \theta^{obo}_{ooc} = \theta'.\mu(o, a, h).\mu(b, b, h).\mu(o, c, h)\\ \text{at } S,\ \theta^{abc}_{ooc} = \theta'.\mu(a, a, h).\mu(b, b, h).\mu(c, c, h)\end{array}$$

$$\text{whence } \frac{\theta_{ooc}.\theta_{aoo}.\theta_{obo}}{\theta_{abc}} = [\theta'.\mu(o, a, h).\mu(o, b, h).\ \mu(o, c, h)\ ]^2 = [\theta_{ooo}]^2$$

(3) *Three mid-edge temperatures and common corner temperature* (*points P, Q, R, and S, Fig.* 2)—The identities are :

$$\begin{array}{l}\text{at } P,\ \theta_{abo} = \theta'.\mu(a, a, h).\mu(b, b, h).\mu(o, c, h)\\ \text{at } Q,\ \theta^{aoc}_{abo} = \theta'.\mu(a, a, h).\mu(o, b, h).\mu(c, c, h)\\ \text{at } R,\ \theta^{obc}_{abo} = \theta'.\mu(o, a, h).\mu(b, b, h).\mu(c, c, h)\\ \text{at } S,\ \theta^{abc}_{abo} = \theta'.\mu(a, a, h).\mu(b, b, h).\mu(c, c, h)\end{array}$$

$$\text{whence } \frac{\theta_{abo}.\theta_{aoc}.\theta_{obc}}{[\theta_{abc}]^2} = \theta'.\mu(o, a, h).\mu(o, b, h).\mu(o, c, h) = \theta_{ooo}$$

(4) *Temperature measurements on one face only*—Consider the mid-plane surface line PN (Fig. 2). The only identity that can be obtained is :

$$\theta_{xbo} = \theta'.\mu(x, a, h).\mu(b, b, h).\mu(o, c, h)$$

for all values of x between o and a. On substituting values of x, no combination of the resulting identities will give the centre temperature θ_{ooo}, unless $\theta_{obo} = \theta_{aoo}$, which occurs with a square section (*i.e.*, $a = b$) and with identical heat transfer coefficients for both surfaces. In such conditions, the centre temperature can be obtained from $[\theta_{obo}]^2/\theta_{abo}$, as in (1).

For other rectangular sections, provided that the heat transfer coefficients are the same for all faces, the

Table I

CALCULATED TEMPERATURES OF COOLING INGOT

Time from Start, hr.	From Russell Tables			From Mid-edge and Mid-face Temperatures
	Mid-edge, °C.	Mid-point of Long Face, °C.	Centre, °C.	Centre, °C.
1	509	779	1139	982
2	376	655	989	895
3	295	550	832	784
4	238	458	691	671
6	160	314	477	469
8	114	217	322	322
10	81	150	219	219

centre temperature can be obtained if the heating (or cooling) period is long enough, when only the first term is significant in the series given in the Appendix for the functions $\mu(x, a, h)$, etc. The temperature at each point along the surface line PN is then given by an expression of the form

$$\theta_{xbo} = \theta'.C\cos fx.C'\cos f'b.C'',$$

where C, C', and C'' are constants, and f and f' are the first positive roots of

$$f\tan fa = h/K,$$
$$\text{and } f'\tan f'b = h/K.$$

The required centre temperature, $x = y = 0$, is given by:

$$\theta_{ooo} = \theta'.C.C'.C'' \text{ (since } \cos 0 = 1)$$
$$= \frac{\theta_{obo}}{\cos f'b} \quad \ldots\ldots(1)$$

and is obtained as follows:

(i) Calculate the ratio mid-edge temperature/mid-face temperature,

$$\frac{\theta_{abo}}{\theta_{obo}} = \cos fa$$

(ii) Obtain fa (radians) from cosine tables

(iii) Obtain ha/K from a table or graph of the form $M\tan M = H$, substituting fa for M and ha/K for H

(iv) Calculate hb/K

(v) Obtain $f'b$ from the table or graph in (iii), substituting hb/K for H and $f'b$ for M

(vi) Obtain $\cos f'b$ from cosine tables, and substitute in equation (1).

A graph of the form $\cos M$ *vs.* $M\tan M$ has been used to reduce the number of steps in this calculation, and provides the basis for the nomogram, Fig. 3. The ratio of the mid-edge and mid-face temperatures relative to the surroundings gives a point $(\theta_{abo}/\theta_{obo})$ on the bottom scale of the grid. Lines are then drawn as follows:

(i) Vertically to meet the curve on the grid

(ii) Horizontally to the right-hand border of the grid

(iii) Through a point on the central scale corresponding to the length a of the face whose temperatures are measured, to meet the right-hand scale, which shows the value of h/K

(iv) From the right-hand scale back through the central scale, at a point corresponding to length b of the second face, to meet the right-hand border of the grid

(v) Horizontally to meet the curve

(vi) Vertically from the curve to the bottom scale.

This procedure gives the ratio of the known mid-face temperature to the centre temperature, *i.e.*, $\theta_{obo}/\theta_{ooo}$. It should be noted that the ratio of the mid-edge temperature to mid-face temperature, $\theta_{abo}/\theta_{obo}$, will be unity at zero time, and tends to a limiting value, equal to $\cos fa$, as t increases. If, in practice, the ratio is found to decrease on successive readings, the calculated centre temperatures will be in error.

Example

Table I shows the comparison between centre temperatures calculated from the Russell tables and those calculated from mid-face and mid-edge temperatures, as in (4), for the following conditions:

Cross-section of ingot:	122 cm. × 61 cm. (4 ft. × 2 ft.)
Thermal conductivity:	0·002 cal./cm. sec. °C. (20 B.Th.U./ft. hr. °F.)
Thermal diffusivity:	0·05 sq. cm./sec. (0·2 sq. ft./hr.)
Heat transfer coefficient:	0·0027 cal./sq. cm. sec. °C. (20 B.Th.U./sq. ft. hr. °F.)
Initial temperature of ingot:	1200° C. (2192° F.)
Constant temperature of surroundings:	20° C. (68° F.)

Heat flow in the third dimension has been neglected; *i.e.*, the ingot is assumed to be infinitely long, or to be insulated at each end, to simplify this example.

For these conditions, there is good agreement between the exact and approximate methods at the later stages. However, the difference between mid-edge and mid-face temperatures is small, and errors in temperature measurements could seriously affect the ratio.

AN EMPIRICAL GRAPHICAL METHOD

Method

If the surface temperatures of the mid-plane of an ingot are plotted against the square of the distance of each point from the centre, extrapolation to zero distance will indicate the approximate centre temperature.

Derivation

Table II gives experimental results for the surface temperatures of the mid-plane of an ingot 45 in. × 20 in. cross-section, and 75 in. long. The measurements were obtained by means of a contact thermocouple, 51 min. after stripping, and 2 hr. 51 min. after teeming.

The temperature distribution over the long face is approximately parabolic; thus the graph of temperature against the square of the distance from the centre of the ingot is a straight line, approximately (*see* Fig. 4). The temperature distribution over the short face, also, may be assumed approximately parabolic, and this mid-face temperature, when plotted

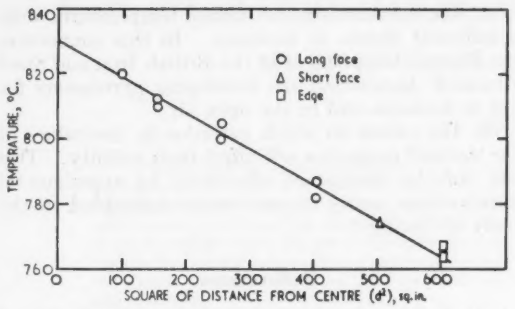


Fig. 4—Ingot surface temperatures

Table II

SURFACE TEMPERATURE MEASUREMENTS

	Distance from Centre Line of Face, in.	Temp., °C.
Long face	22·5	767
	17·5	782
	12·5	805
	7·5	810
	0	820
	7·5	812
	12·5	800
	17·5	787
	22·5	765
Short face	10	765
	0	775

against the square of its distance from the centre, lies on the same straight line. The result is an empirical equation :

$$\theta_{xbo} = \theta_{ayo} = Cd^2 + C' \quad \text{.....(2)}$$

where d = distance from centre, in.

Equation (2) states that surface temperatures at points equidistant from the centre are the same, and implies that the heat flow is approximately radial and that the isotherms approximate to circles about the centre. If this is so, then the centre temperature will be obtained from equation (2) when $d = 0$, *i.e.*,

$$\theta_{ooo} = C'.$$

From Fig. 4, the equation of the straight line is found to be :

$$\theta = -0{\cdot}11d^2 + 830,$$

so that the centre temperature will be approximately 830° C.

Assessment

It can be shown only by direct measurement that the actual centre temperature θ_{ooo} is identical with the constant C' ; however, the extent to which the equation

$$\theta_{xbo} = \theta_{ooo} + Cd^2 = \theta_{ooo} + C(x^2 + b^2)$$

agrees with the formal mathematical solution can be assessed for selected numerical values, by the method outlined on p. 72.

This has been carried out for an ingot of dimensions 1 ft. × 2 ft. × 4 ft. (30·5 cm. × 61 cm. × 122 cm.), assumed to be at a uniform initial temperature of 1500° C., and to have constant average thermal properties :

Thermal conductivity : 0·075 cal./cm. sec. ° C. (18 B.Th.U./ft. hr. ° F.)

Thermal diffusivity : 0·05 sq. cm./sec. (0·19 sq. ft./hr.)

Heat transfer coefficient : 0·00115 cal./sq. cm. sec. ° C. (8·5 B.Th.U./sq. ft. hr. ° F.)
0·00057 cal./sq. cm. sec. ° C. (4·2 B.Th.U./sq. ft. hr. ° F.)
0·00029 cal./sq. cm. sec. ° C. (2·1 B.Th.U./sq. ft. hr. ° F.)

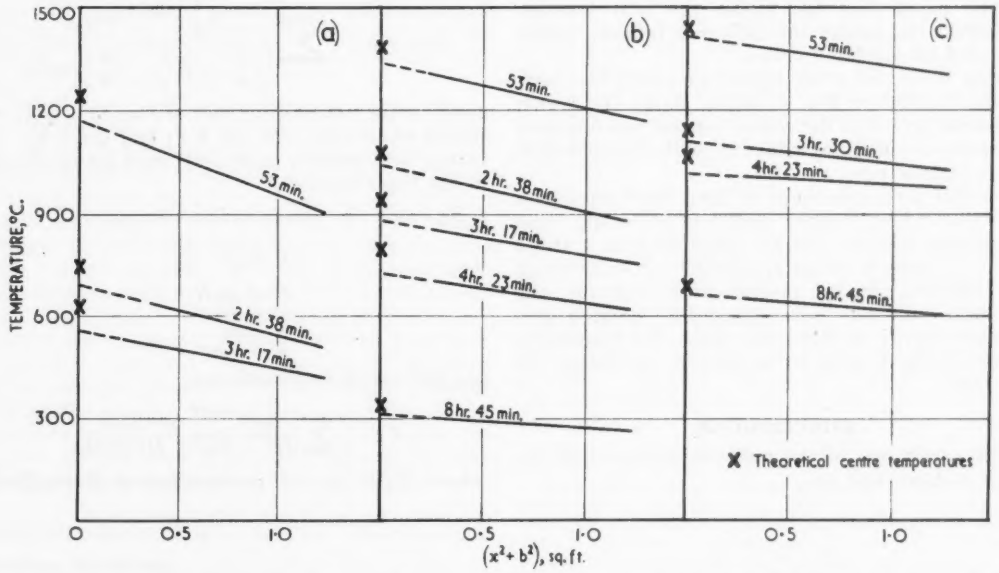


Fig. 5—Temperature distribution in cooling ingot for varying heat transfer coefficients. (*a*) 0·00115 (8·5), (*b*) 0·00057 (4·2), (*c*) 0·00029 (2·1). (Figures in brackets refer to f.p.h. system of measurement)

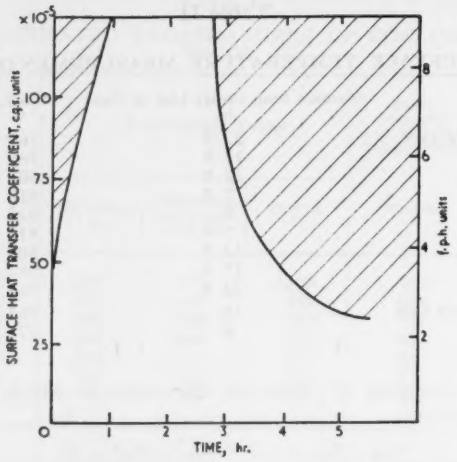


Fig. 6—Region (unshaded) in which linear extrapolation may be used to determine the centre temperature to 5% accuracy

Figures 5*a–c* show the results for different cooling periods. This method gives one line for each value of time; the points do not always lie exactly on a straight line, but the lines drawn in Figs. 5*a–c* represent the best straight lines through the values of the theoretical surface temperatures. Individual points are not distinguishable, because of the thickness o the lines.

The theoretical centre temperature determined from the tables can then be compared with the value obtained by extrapolating the straight line. For example, at 53 min. cooling time (Fig. 5*a*) the centre temperature obtained by extrapolation is 1170° C., compared with a theoretical value of 1250° C. It will be noted that the higher the heat transfer coefficient, the greater the difference between calculated and extrapolated values.

From these and other typical graphs it has been possible to deduce Fig. 6, which shows the region (unshaded) in which the centre temperature obtained by extrapolation agrees within 5% with the theoretical centre temperature.

For this particular shape of ingot there must be a low value of heat transfer coefficient at cooling times longer than 3 hours, but for times between 1 and 3 hours the method seems applicable to a wider range of conditions. In the present work, however, one size ratio only has been considered; from a preliminary survey of other size ratios, the boundaries shown in Fig. 6 seem to be sensitive to changes in this ratio.

CONCLUSIONS

The application of the methods discussed in this paper is dependent on:

(1) The measurement of surface temperatures with a sufficient degree of accuracy. In this connection the Physics Department of the British Iron and Steel Research Association are developing pyrometers for use in furnaces and in the open air.

(2) The extent to which variation in the values of the thermal properties will affect their validity. This can only be determined effectively by experimental observations, using thermocouples embedded in the body of the ingot.

References

1. H. S. Carslaw and J. C. Jaeger: "Conduction of Heat in Solids." Oxford, 1947: Clarendon Press.
2. T. F. Russell: *Special Report No.* 14, p. 149; 1936, The Iron and Steel Institute.
3. W. H. McAdams: "Heat Transmission." London and New York, 1942: McGraw-Hill Book Co., Inc.

APPENDIX

Let a, b, c = dimensions from the centre to the surfaces of a rectangular parallelepiped
K = thermal conductivity, constant
D = thermal diffusivity, constant
h = heat transfer coefficient at surface, constant
θ' = uniform initial temperature
θ'' = temperature of surroundings, constant
t = time.

Then at any time, the temperature θ of a point (x, y, z) in the ingot is given by:

$$\frac{\theta - \theta''}{\theta' - \theta''} = \mu(x, a, h).\mu(y, b, h).\mu(z, c, h)$$

where

$$\mu(x, a, h) = \sum_{n=1}^{\infty} \frac{2\frac{h}{K} e^{-Df_n^2 t} \cos f_n x}{\left[\left(\frac{h^2}{K^2} + f_n^2\right)a + \frac{h}{K}\right]\cos f_n a}$$

and f_n is the nth positive root of $f \tan fa = h/K$, with similar expressions for $\mu(y, b, h)$ and $\mu(z, c, h)$. The surface heat transfer coefficients need not be the same in the three functions.

By using the dimensionless parameters

$$U = \frac{\theta - \theta''}{\theta' - \theta''}$$
$$H = ha/K$$
$$T = Dt/a^2$$
$$M = fa$$
$$R = x/a,$$

$\mu(x,a,h)$ can be expressed as:

$$U_x = \sum \frac{2He^{-M_n^2 T} \cos M_n R}{(H^2 + M_n^2 + H)\cos M_n}$$

where M_n is the nth positive root of $M \tan M = H$.

Use of Aluminium in Hot-Dip Galvanizing

By M. L. Hughes, M.Sc., F.R.I.C., F.I.M.

SYNOPSIS

The first section of this report consists of a review of the somewhat contradictory views expressed in the literature on the subject of aluminium additions in hot-dip galvanizing. The advantages claimed for this practice include improved lustre, diminished rate of bath oxidation, increased corrosion resistance of the coating and, with heavier additions, the elimination of the usual iron–zinc alloy layers. The last is the most important since it has a marked effect on the bending properties. Certain disadvantages also arise when aluminium is used, notably fluxing difficulties. The statements made in the literature regarding these advantages and disadvantages are discussed, and the theories put forward to explain the action of aluminium in producing alloy-free coatings are reviewed.

The second section describes experiments to determine the minimum amount of aluminium needed to eliminate alloy layers or to reduce these to such an extent that adequate bending properties are obtained. Four steels have been tested under various dipping conditions. In most of the published work immersion times were much longer than those used in sheet galvanizing and in many cases the temperatures were very high. The present work has therefore been limited to shorter immersion times and to the normal range of operating temperatures.

Current theories on the mechanism by which alloy-free coatings are produced from baths containing aluminium are shown to be incorrect, and it has been found that, under suitable conditions, an alloying process different from the normal one may occur.

REVIEW OF PREVIOUS WORK

THE addition of small amounts of aluminium to galvanizing baths was advocated many years ago, because increased lustre of the product and reduced loss of zinc by atmospheric oxidation resulted. Small additions up to 0·05%, generally about 0·01%, are often made by galvanizers but not, usually, for ordinary sheet galvanizing.

The addition of larger amounts has been advocated by some workers, mainly by Continental galvanizers,[6, 7, 21, 22, 23] because of the marked change in coating structure and properties, resulting in a reduced tendency to flaking on bending. Such additions are, however, accompanied by operational troubles—notably fluxing difficulties. Contradictory statements on the merits of large additions of aluminium exist in the literature. The present author has shown that galvanized coatings prepared by advocates of this practice contain very little aluminium and have only mediocre properties.

The author's earlier work showed a marked change in structure and an improvement in bending properties, by the addition of 0·18% of aluminium. These results were in agreement with those of some American[17] and German workers,[14, 15] although the author's aluminium additions were rather lower. The results, however, contradicted earlier British work in which much heavier additions were said to be necessary[9]. Some German workers also have recommended much heavier additions. The earlier results of the author, however, have been fully substantiated in later work, described in this paper. The review of the literature on the subject is not exhaustive but has been prepared to show the present state of our knowledge of this important aspect of galvanizing, and to stress the need for further work to elucidate some of the difficulties and contradictions.

ADVANTAGES OF ALUMINIUM ADDITIONS

Corrosion Resistance

An American patent of 1891[1] covers the addition of 4 lb. of aluminium per ton of zinc, equivalent to 0·01%, to hot-dip galvanizing baths. It was claimed that this addition imparted extra lustre to the coating and increased its resistance to corrosion. The first of these claims is generally accepted and small additions are made in general galvanizing and in tube galvanizing, but not usually to mechanized sheet galvanizing units. Statements in support of this practice have been made by Forny,[2] Frochlich,[3] Matteson,[4] Brayton,[5] Thews,[6] Bablik,[7] Gordet,[8] and Hall and Kenworthy.[9] These workers agree that 0·01–0·02% of aluminium is sufficient to produce the desired result. Bablik and Gotzl[10] add that if the time of immersion exceeds 10 min. the brightness is lost; such prolonged immersion is seldom required.

Brayton[5] stated that the increased brightness persists for some time. Samples containing 0·05% of aluminium which the writer has had for nearly three years have kept their lustre better than samples containing no aluminium. This suggests that aluminium increases the resistance to atmospheric oxidation, possibly by the formation of an invisible, impermeable, and resistant film, but this suggestion is not always supported by corrosion tests.

According to Bablik[11] aluminium-alloyed zinc and iron–zinc alloys have approximately the same resistance to atmospheric corrosion as 'pure' zinc, but have less resistance to corrosive liquids. Thews[6] on the other hand, considers that corrosion resistance is increased by small additions of aluminium. Coatings containing 1·4% and 3% of aluminium were included by Gilbert[12] in a systematic study of the resistance of zinc coatings to atmospheric corrosion but the presence of the aluminium did not appreciably affect the corrosion. Burkhardt[13] states that corrosion resistance is reduced by the addition of aluminium,

Paper MW/C/56/49 of the Coatings Research Committee of the Mechanical Working Division of the British Iron and Steel Research Association, received 8th March, 1950. The views expressed are the author's and are not necessarily endorsed by the Committee as a body.

Mr. Hughes is on the staff of the Association at Sketty Hall, Swansea.

the lead content of the zinc being an important factor.

The addition of 0·05% of aluminium[6] or less is considered to produce a thin resistant film which retards the atmospheric oxidation of molten zinc. The presence of aluminium in the general galvanizing bath where the surface of the molten metal is continually disturbed, should lead to considerable economies. In practice these are appreciably less than would be expected.

Alloy Thickness

With larger additions of aluminium, the rate of formation of iron–zinc alloys is affected, causing marked changes in the structure and properties of the coating. This is probably the most important aspect of aluminium additions and the one in which there is the most divergence of opinion.

Thews[6] considers that at least 0·10% or even 0·15% of aluminium is necessary for an appreciable reduction in alloy thickness, although Scheil and Wurst[14] report a reduction with only 0·01%. These latter workers, however, state that 0·16% of aluminium reduces the alloy layers to 0·8% of the usual thickness, *i.e.*, almost complete elimination. The aluminium addition necessary to eliminate alloy layers is generally quoted as 0·15–0·3%. Bablik[15] in general, favours a 0·2–0·3% addition, 0·2% being sufficient if the temperature does not exceed 430° C. and the immersion time, 30 sec. In 1938 Bablik and Gotzl[10] stated that 0·15% of aluminium had little or no effect, and in 1941[16] they reported that 0·3% of aluminium is needed at 445° C. Rowland[17] suggests 0·10–0·3%, and Pierce[18] states that 0·2% either almost, or completely, eliminates the alloy layer. Figure 17*a* of a paper by Finkeldey[19] shows the absence of alloy layers after galvanizing in a bath containing 0·2% of aluminium and Sirotkin[20] recommended 0·2–0·3% of aluminium. Despite the apparent agreement that 0·2–0·3% is sufficient, heavier additions of aluminium have been recommended. By 1947 Bablik[7] had raised his upper figure to 0·4%; Lvov and Shlegol,[21] in 1940 suggested 0·5% of aluminium. Thews[6] reported that in some cases up to 0·5% may be needed. An anonymous writer[22] stated that 0·6–0·8% should be present. A patented French process of hot-dip galvanizing[23] is said to include the addition of 1·0% of aluminium. In a systematic study of the variables of the galvanizing process, Hall and Kenworthy[9] concluded that 0·6% of aluminium was needed to eliminate alloy layers, although as little as 0·06% was observed to effect some reduction.

The author has found that 0·15–0·18% of aluminium eliminates alloy layers under sheet galvanizing conditions, while, under suitable conditions, as little as 0·10% may effect almost complete elimination. The variation in the recommended aluminium addition may be attributed, in part, to differences in steel composition, bath composition, temperature, and time of dipping.

Local formations of alloy occur quite frequently in coatings containing about 0·15% of aluminium. These ' mushroom ' growths show several layers and there is often a marked attack on the steel base[16] (*see* Figs. 11*b* and *c*). Such irregular formations of the alloy layers are likely to have an adverse effect on the bending properties of the coating.

The mechanism of this inhibition of alloy formation (by addition of such small amounts of aluminium) has not yet been satisfactorily explained. At least three explanations have been proposed. Rowland,[17] suggests the formation of an aluminium oxide membrane on the surface of the steel which restrains the rate of diffusion of both iron and coating metal. He accounts for the local formations of alloy by the presence of discontinuities, or punctures, in the film. Where these occur the local growth of the alloy would be very rapid. Bablik,[11] on the other hand, considers that the aluminium causes an induction period in the reaction between the zinc and the steel base. He has likened it[24] to the initial inhibiting period when a metal is immersed in acid. This theory does not explain the rapid formation of the local growths, unless they are regarded as analogous to the ' active sites ' in other surface phenomena.

A third explanation of the absence of alloy layers has been proposed by Hall and Kenworthy.[9] For small amounts of aluminium up to 0·06% and for short immersion times, they found a reduction in the weight of coating without any marked change in structure. They support the idea of an induction period suggesting that aluminium delays the start of the reaction for a short time. When the aluminium content of the bath exceeded about 0·06% they found a marked increase in alloy thickness and in thickness of total coating. This persisted until the aluminium reached 0·6–0·8%. At this stage the thickness of the alloy layers and that of the total coating suddenly dropped to values much less than those previously obtained. Only at 1% of aluminium was complete freedom from alloy obtained; at the customary 0·2–0·3% of aluminium, with a 30-sec. immersion, the alloy was almost the same as with an unalloyed bath; after 1-min. immersion the alloy was actually greater. Hall and Kenworthy report that at 0·6–0·8% of aluminium the alloy layer appeared to break up and float away as soon as it was formed. This idea explains the greater loss of weight of the steel base when aluminium was added to the bath. These workers refer to " odd crystals of alloy . . . detached and trapped in the zinc." Their photomicrographs do not show this clearly, and since odd crystals of alloy may be found in the zinc layer under normal circumstances, there is insufficient direct evidence in their paper to support the suggestion of complete falling away of the alloy layer. From the present author's experiments there is ample evidence of loose crystals in the coating, but their origin and nature are not yet completely understood.

The rate of attack on the basis steel is linked very closely with the extent of alloy formation, and has an important bearing on the probable life of galvanizing kettles. Daniels[25] showed a slightly increased attack with only 0·05% of aluminium. Tests carried out at 461° C., using 0·10% of aluminium, showed a 27% increase in attack over that for pure zinc; the immersion times for these tests appear to have been 30 min. Bablik and Gotzl,[10] on the other hand, stated that less than 0·15% of aluminium has practically no effect on the amount of iron taken into the

bath, or on the zinc taken up by the article being galvanized, or on the structure of the coating. In Fig. 23 of a paper by these workers in 1941 the addition of 0·2% of aluminium to electrolytic zinc is shown to reduce the attack on armco iron at all temperatures between 460° C. and 500° C., even with an immersion time of 1 hr. The shape of their curve was roughly similar to that for pure zinc, *i.e.*, a marked increase of attack at 490–500° C. Bablik and Gotzl expressed some uncertainty about their results ; a very different curve is given by Bablik[26] (Fig. 126*b*) in his textbook published in the same year. This curve suggests that 0·1% of aluminium increases the attack on iron between 440° C. and 495° C., the attack being twice as great at 480° C. for an immersion time of 1 hr. An earlier table in this book shows that additions of aluminium between 0·025% and 0·20% reduce both the attack on the iron and the amount of zinc coating taken up, provided that the immersion time is not more than 2 min.

Although Daniels[25] states that the small additions of aluminium normally made for improving the appearance of coatings will have no effect on the life of galvanizing kettles, it is possible that local overheating in the presence of aluminium may be more serious than with baths free from aluminium. The results presented in Fig. 6 of a paper by Hall and Kenworthy[9] show a progressive increase in attack with increase in aluminium content and with increase in time. The sudden fall in alloy thickness at 0·6–0·8 of aluminium previously referred to, may be the result of almost complete loss of adherence to the basis material and may have an important bearing on pot life. In such highly alloyed baths, the alloy may form rapidly and may fall away into the bath, giving no protection. On this theory dross formation should be greater in aluminium-alloyed baths, but this does not seem to occur in practice.

The general opinion is that owing to the suppression of alloy formation there should be a reduction in dross production ; this reduction appears to be less than expected. Bablik[27] states that aluminium reduces dross formation ; Brayton[5] reports that additions in general, including aluminium, do not materially reduce dross production. Gordet[8] considers that aluminium slightly increases the amount of ' hard zinc ' formed. The absence of any reports of appreciable increases in dross production when making alloy-free coatings casts doubt on the idea that the alloy is formed but rapidly floats away.

Bending Properties

The chief advantage claimed for alloy-free coatings containing aluminium is the improved bending properties, flaking being much reduced or prevented. Complete absence of alloy does not appear to be necessary to obtain adequate bending quality. But it is not quite clear why these coatings behave so well in the bend test ; either the zinc bends much more readily, or its ' adhesion ' to the steel base is appreciably greater than that of the alloy layers. Bablik[28] considers that the intrinsic ' adhesion ' of an alloy-free coating is less, but that the bending property is much greater. There is general agreement in the literature regarding this advantage of aluminium additions, although Imhoff[29] has suggested that aluminium should be avoided for good bending qualities. In earlier reports he advocated small additions, quoting narrow ranges of composition for galvanizing different articles.[30, 31]

Fluidity

Other advantages obtained by the use of aluminium include the elimination of yellow coatings of tin or antimony[6, 32, 33] and an increase in the fluidity of the bath. The latter does not necessarily mean that aluminium has any marked effect on the viscosity of molten zinc.

DISADVANTAGES OF ALUMINIUM ADDITIONS

When the aluminium addition exceeds that necessary for imparting lustre, namely, 0·01–0·02%, trouble is encountered.

Within the range 0·03%[9] and 0·05% of aluminium, black spots may appear on the product. These spots may be associated with the injurious effect of aluminium on the fluxing reaction ; the effect becomes apparent when the aluminium content reaches 0·05% or more. The smaller additions may merely diminish fluxing efficiency so that certain spots are not coated properly.[34] Brayton[5] considers that aluminium " diffuses through the metal with great rapidity and its power to bring the dirt up causes black spots on the sheets," and he concludes that aluminium should not be added to a sheet pot. His objection to aluminium is supported by the experience of South Wales sheet galvanizers who have long abandoned the practice of using aluminium. The suggestion by Matteson[4] that aluminium oxide forms on the exit rolls causing oxide spots and unsaleable sheets, is contradicted by the success of the Sendzimir process in which aluminium is successfully used. Flux is not used in this process ; this supports the idea that the spots are associated with flux troubles. Others have suggested that the flux becomes sticky and adheres to the sheet. Thews[6] has shown that aluminium affects the physical nature of the flux and can cause it to become slimy.

Aluminium additions greater than about 0·05% make it imposssible to maintain the usual flux blanket. Bablik[28] stated (in 1948) that " no flux has yet been developed which would form a liquid layer on a zinc bath alloyed with aluminium." This statement ignores the fluoride fluxes, introduced by Liban[35] from 1927 onwards, and which Continental galvanizers have employed with some success. The only alternative to the use of such special fluxes is the ' dry ' process in which the articles to be galvanized are prefluxed in a solution of zinc ammonium chloride, or zinc chloride alone, and dried before immersion in the molten bath. Poor coating may still result if there is appreciable aluminium in the bath. It has been suggested[36] that fluxing with ammonium chloride *vapour* will permit the use of up to 0·1% of aluminium in the bath.

The heavier additions of aluminium up to 1·0% which have been recommended, may introduce brittleness in the coating and perhaps other disadvantages. Thews[6] states that " where aluminium contents exceed a certain critical maximum, apart from deterio-

rating mechanical properties of the coating, they exert a pronounced unfavourable influence on spangle, as well as on the surface generally." Richards,[37] described a galvanized wire as having a " particularly brittle coating which flaked in large pieces from the surface." When analysed, this coating was found to contain 1·0% of aluminium; the reported iron content suggests that there was appreciable alloy present. Photomicrographs given in this paper show that coatings found by analysis to contain 0·24%, 0·32%, 0·15%, 0·18%, and 0·13% of aluminium all included appreciable amounts of alloy.

There is a fairly widespread impression that aluminium segregates in the bath, forming an enriched liquid layer at the surface. There appears to be no theoretical reason for this and it is more likely that the additions of zinc–aluminium alloy are not made properly, and that mixing is incomplete. Preferential oxidation of aluminium may occur and an excess of aluminium might exist at the surface as oxide but this is distinct from, and would not explain, the observations referred to above.

Some coatings have been shown, by analysis, to contain appreciably more aluminium than the bath from which they were produced. This appears to support the theory of an aluminium-rich layer at the surface of the bath. However, experimental evidence is given later which attributes the enrichment of the coating in aluminium-containing baths to the formation of an alloy phase considerably richer in aluminium than the original bath.

Other disadvantages associated with the use of aluminium include the reduced thickness and shorter life of coatings free from alloy layers. Also the ' zinc ash ' which is sold as a by-product, is contaminated with aluminium.

EXPERIMENTAL WORK

Preliminary experiments were carried out to check some earlier results, using different steels under a variety of galvanizing conditions. In later tests, to determine the minimum addition of aluminium needed under sheet galvanizing conditions, sheet steel samples were rotated in galvanizing baths containing diminishing amounts of aluminium, and the coatings were examined for bending behaviour and subsequently examined under the microscope.

Some experiments have been carried out to examine the theories for the mechanism of alloy inhibition by aluminium which have been referred to earlier.

EFFECT OF NORMAL ALUMINIUM ADDITIONS

Hot-Dip Galvanizing of Rods

It had been previously found that a bath containing 0·18% of aluminium gave galvanized coatings on cold-reduced sheet steel (about 24 gauge) which were free from alloy layers. The time of immersion was 30 sec. and the temperature 460° C.

Further experiments have been carried out with this bath using rods of armco iron, 0·10% carbon steel, and a steel containing 0·22% of C and 0·10% of Si. Two immersion times were used, 15 sec. and 30 sec. and a temperature of 460° C. Similar tests were also carried out at 430° C. and 490° C. The results are summarized in Table I.

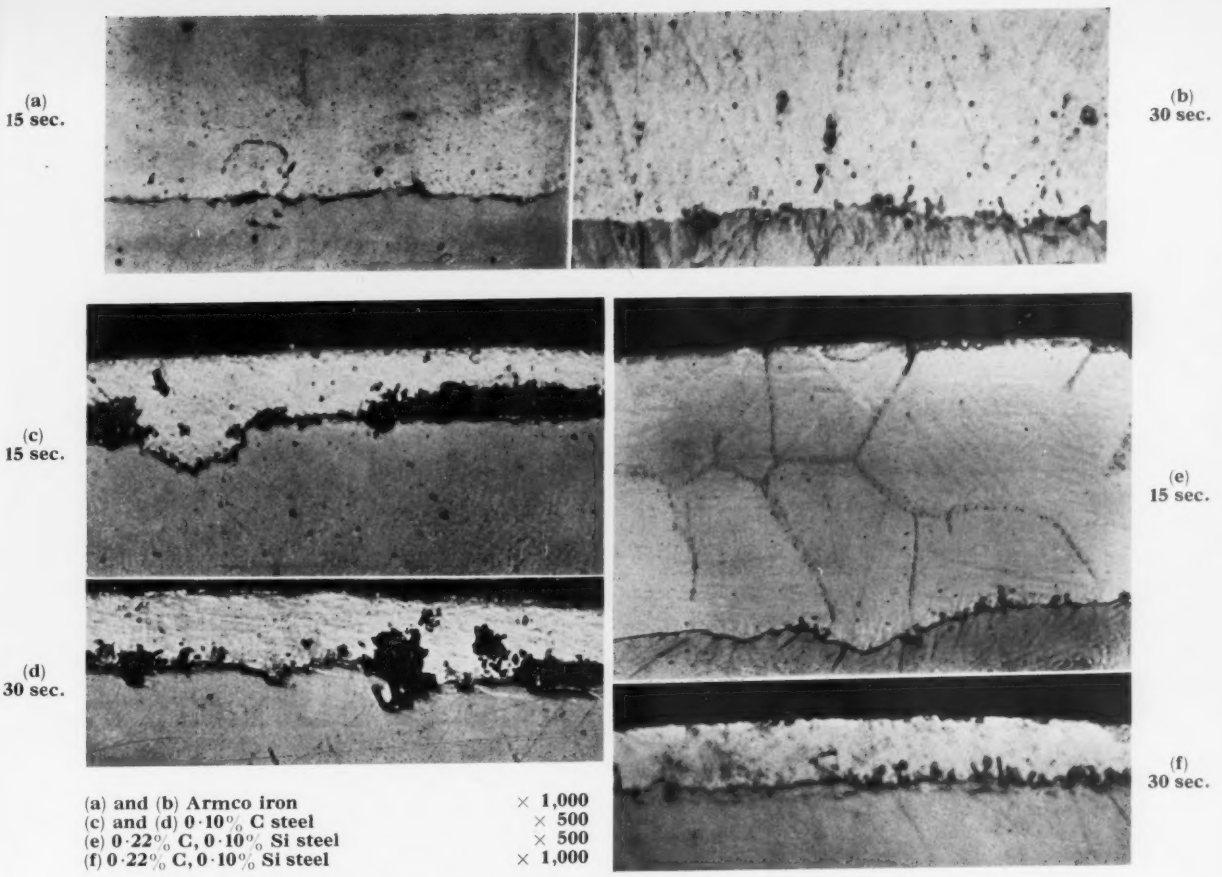
The results obtained with material *C* (0·22% C, 0·10% Si steel) at 460° C. and 430° C. were rather surprising. The increased carbon content, compared with material *B* (0·10% C steel), and especially the presence of 0·10% of silicon, would normally be expected to cause considerably greater alloy formation. As shown in Figs. 1*e* and *f*, and 2*c*, there was negligible alloy formation. After 30-sec. immersion at 490° C. the peculiar behaviour of steel *C* disappeared and an appreciable thickness of alloy of normal appearance formed over most of the surface (*see* Fig. 4*c*). This structure was broken up in places with the formation of small alloy-free zones, (*see* Fig. 4*d*).

Bablik[38] had also observed this effect of silicon ; he found that because of the Si content of the steel (probably about 0·3%), the proportion of aluminium in the bath necessary to prevent interaction at 429° C. is only 0·04% ; with pure iron an aluminium

Table I

INFLUENCE OF STEEL BASE COMPOSITION, TEMPERATURE OF IMMERSION, AND TIME, ON ALLOYING BEHAVIOUR IN A BATH CONTAINING 0·18% OF ALUMINIUM

Steel Base	460° C.		430° C.		490° C.	
	15 sec.	30 sec.	15 sec.	30 sec.	15 sec.	30 sec.
A. Armco iron	Generally very little alloy. Local alloying (*see* Fig. 1*a*)	As 15 sec. but increased local alloying (*see* Fig. 1*b*)	Generally no alloy. Slight local formation (*see* Fig. 2*a*)	Greater tendency to local alloying	Uniform thin duplex layer of alloy (*see* Fig. 3*a*)	Similar to results after 15 sec. (*see* Fig. 4*a*)
B. 0·10% C steel	Definite alloy layers. Some alloy-free spots (*see* Fig. 1*c*)	As for 15 sec. (*see* Fig. 1*d*)	Little or no alloy. Very little local alloying (*see* Fig. 2*b*)	Increased alloy formation but many alloy-free areas	Uniform duplex layer as with armco iron (*see* Fig. 3*b*)	As for 15 sec. but occasional local thickening (*see* Fig. 4*b*)
C. 0·22% C, 0·10% Si steel	Negligible alloy formation (*see* Fig. 1*e*)	A few local growths. Elsewhere a few crystals only (*see* Fig. 1*f*)	No alloy visible (*see* Fig. 2*c*)	Almost entirely alloy-free	Uniform duplex alloy layer; rather thicker than with *A* and *B* (*see* Fig. 3*c*)	Uniform duplex alloy layer, considerably thicker than with *A* and *B* (*see* Fig. 4*c*) Local areas free from alloy (*see* Fig. 4*d*)



(a) and (b) Armco iron × 1,000
(c) and (d) 0·10% C steel × 500
(e) 0·22% C, 0·10% Si steel × 500
(f) 0·22% C, 0·10% Si steel × 1,000

Fig. 1.—Sections of coatings on samples of iron and steel immersed for 15 and 30 sec. Galvanizing temperature 460° C., with 0·18% aluminium bath

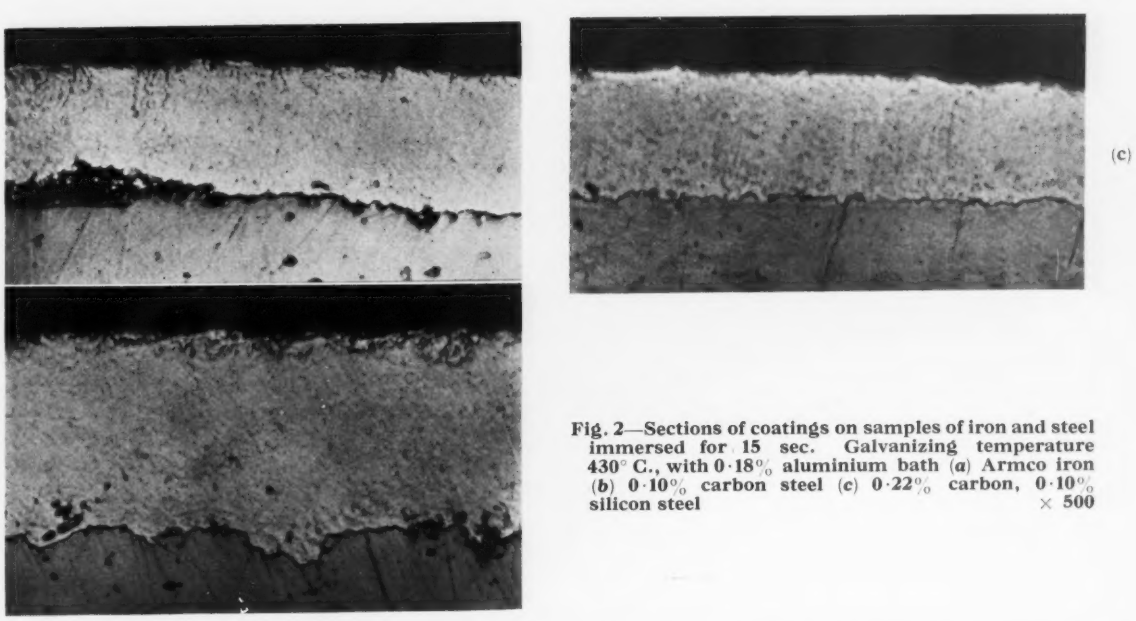


Fig. 2—Sections of coatings on samples of iron and steel immersed for 15 sec. Galvanizing temperature 430° C., with 0·18% aluminium bath (*a*) Armco iron (*b*) 0·10% carbon steel (*c*) 0·22% carbon, 0·10% silicon steel × 500

Etching reagent, Rowland's No. 3, 0·068 g. of picric acid, 20 ml. of ethyl alcohol, 50 ml. water

[*Hughes*

[*To face p.* 80

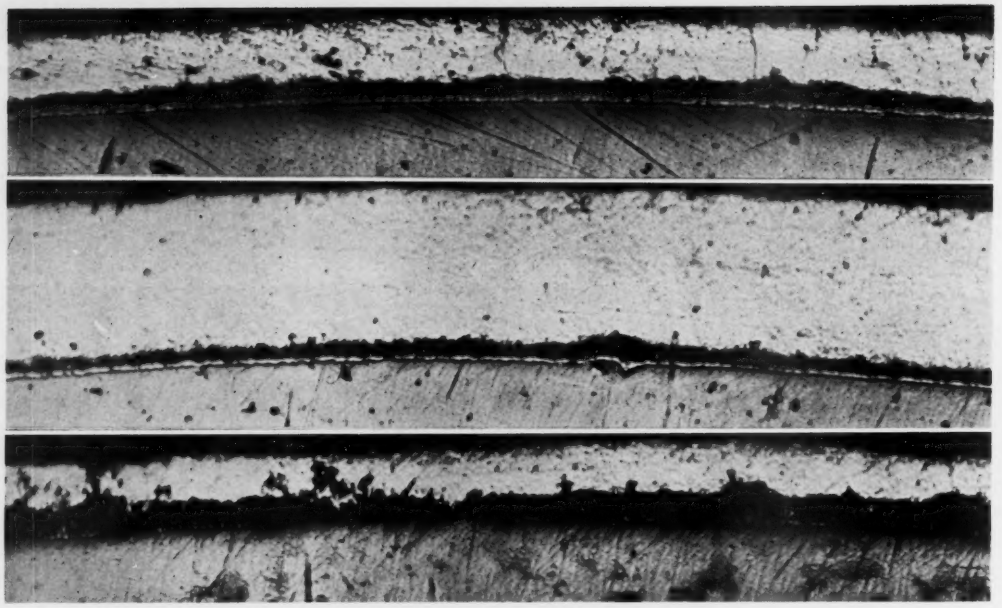


Fig. 3—Sections of coatings on samples of iron and steel immersed for 15 sec. Galvanizing temperature 490° C., with 0·18% aluminium bath (*a*) Armco iron (*b*) 0·10% carbon steel (*c*) 0·22% carbon, 0·10% silicon steel × 500

Fig. 4—Sections of coating on samples of iron and steel immersed for 30 sec. Galvanizing temperature 490° C., with 0·18% aluminium bath (*a*) Armco iron (*b*) 0·10% carbon steel (*c*) and (*d*) 0·22% carbon, 0·10% silicon steel × 500

Etching reagent, Rowland's No. 3, 0·068 g. of picric acid, 20 ml. of ethyl alcohol, 50 ml. of water

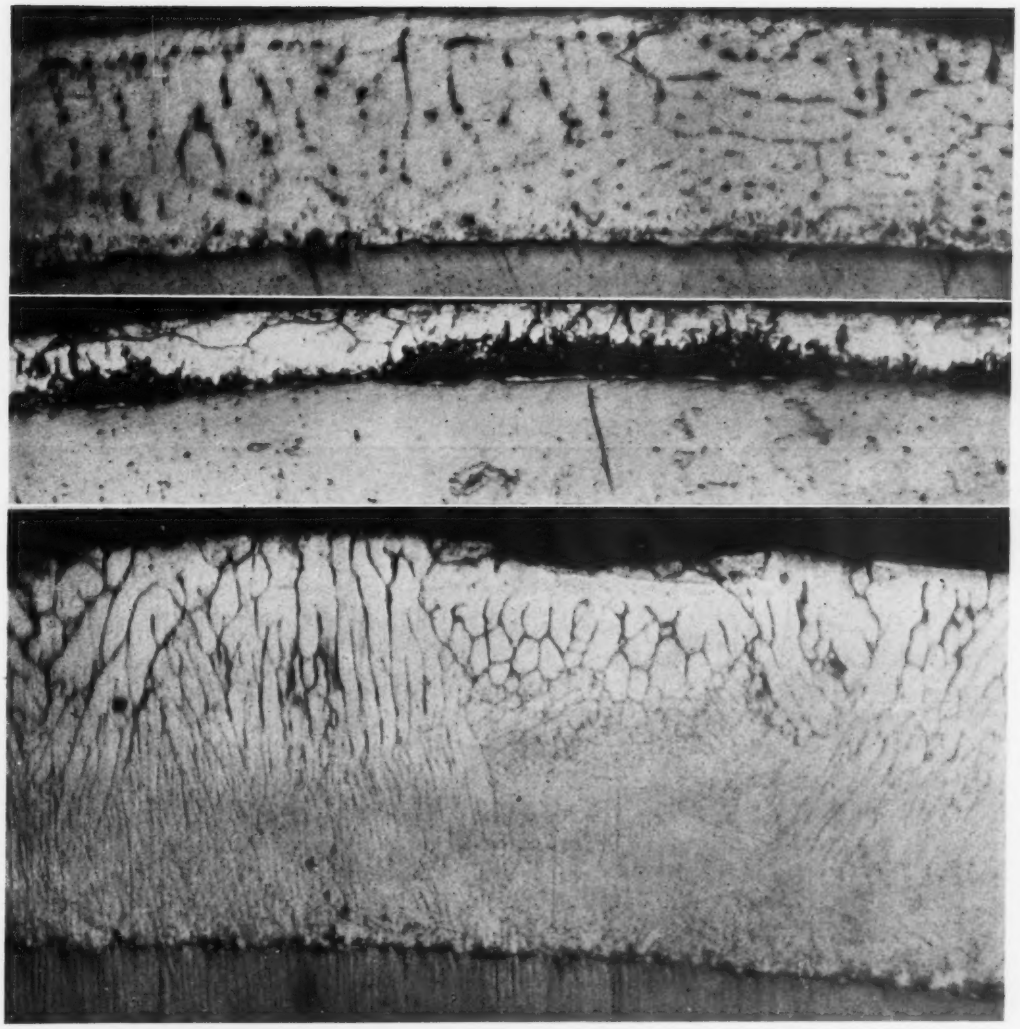


Fig. 5—Sections of coatings on samples of iron and steel immersed for 30 sec. Galvanizing temperature 490° C., with 0·33% aluminium bath (*a*) Armco iron (*b*) 0·10% carbon steel (*c*) 0·22% carbon, 0·10% silicon steel × 500

Etching reagent, Rowland's No. 3, 0·068 g. of picric acid, 20 ml. of ethyl alcohol, 50 ml. of water

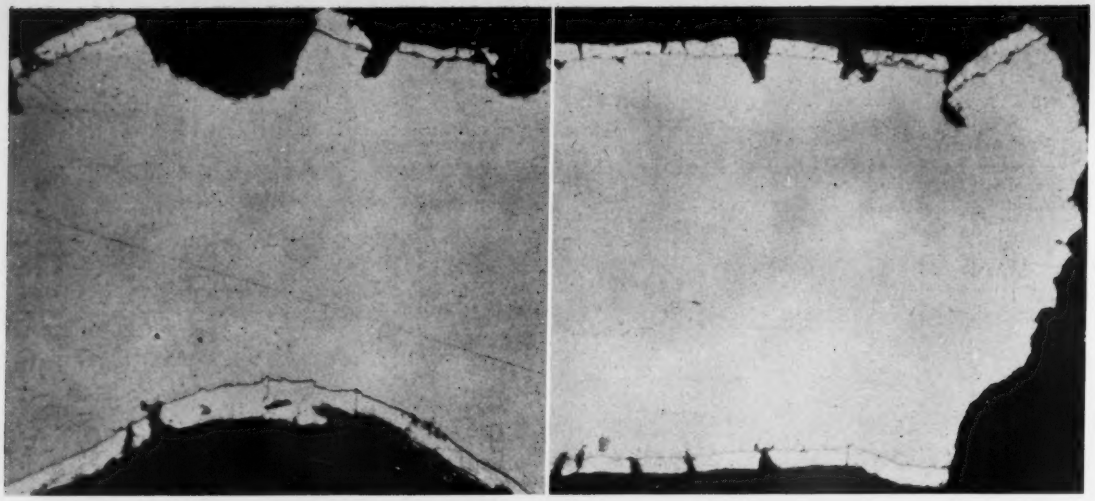


Fig 6—Sections of coatings on samples of cold reduced sheet steel immersed for 15 and 30 sec. Galvanizing temperature 430° C., with 0·10% aluminium baths (*a*) 15-sec. immersion, steel fractured after 22 bends (*b*) 30-sec. immersion, steel fractured after 18 bends. (Both reduced by $\frac{13}{16}$ linear in reproduction) × 125

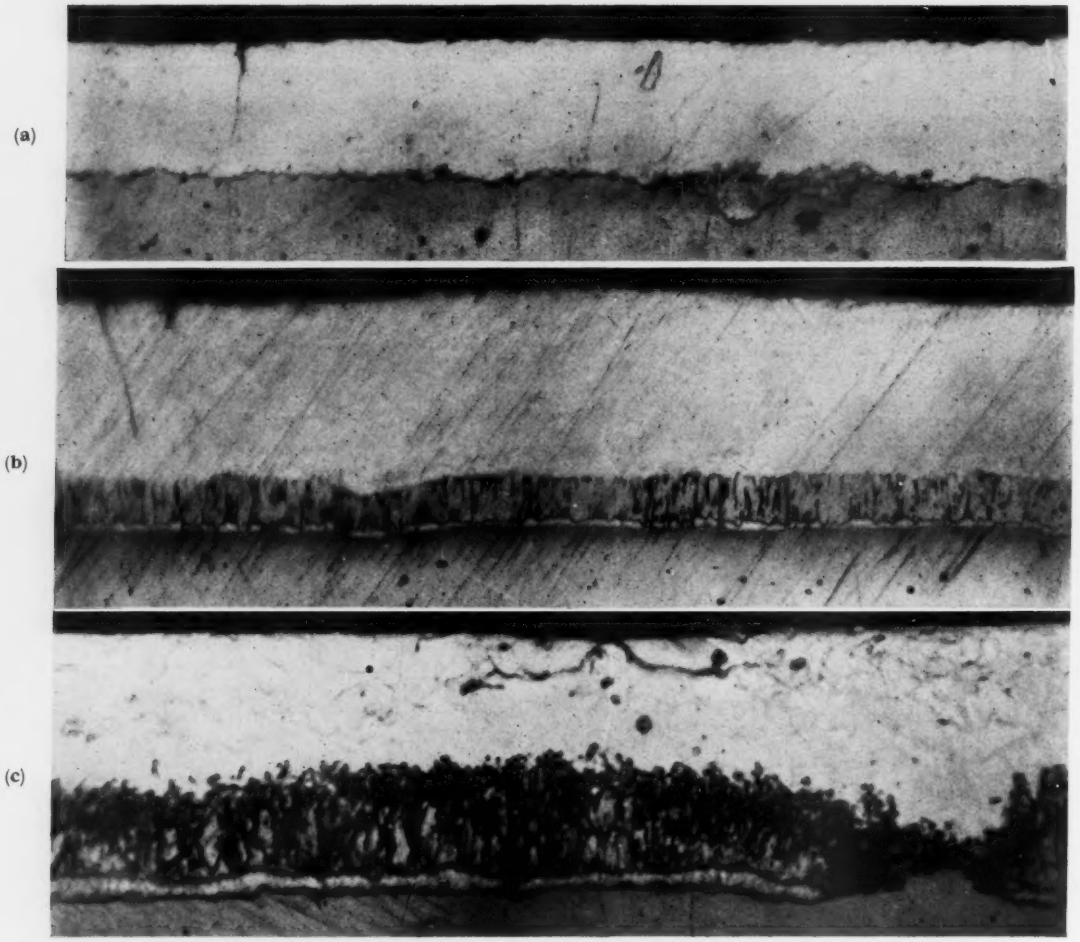
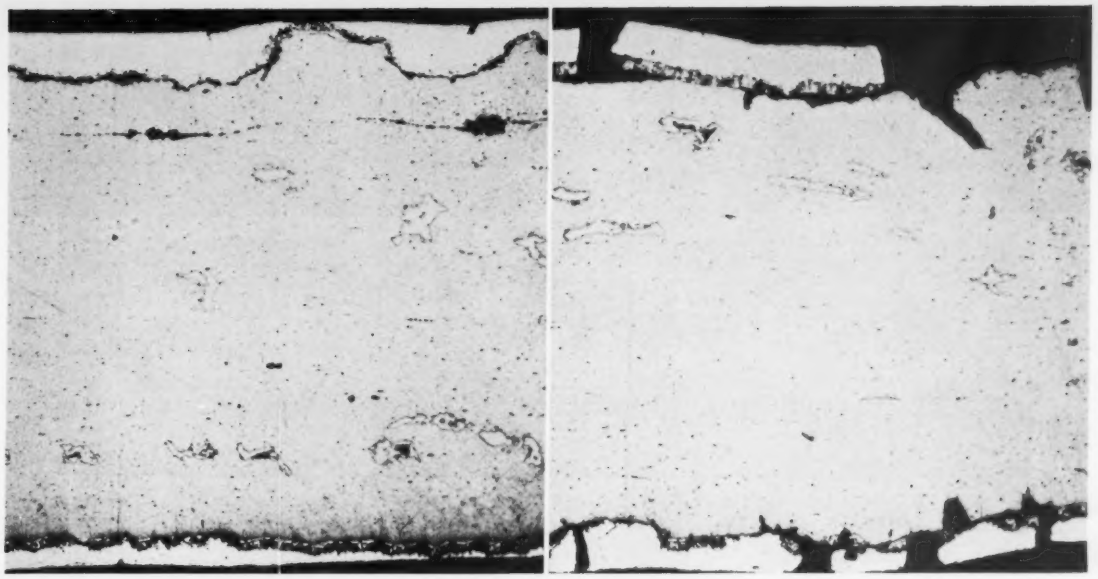


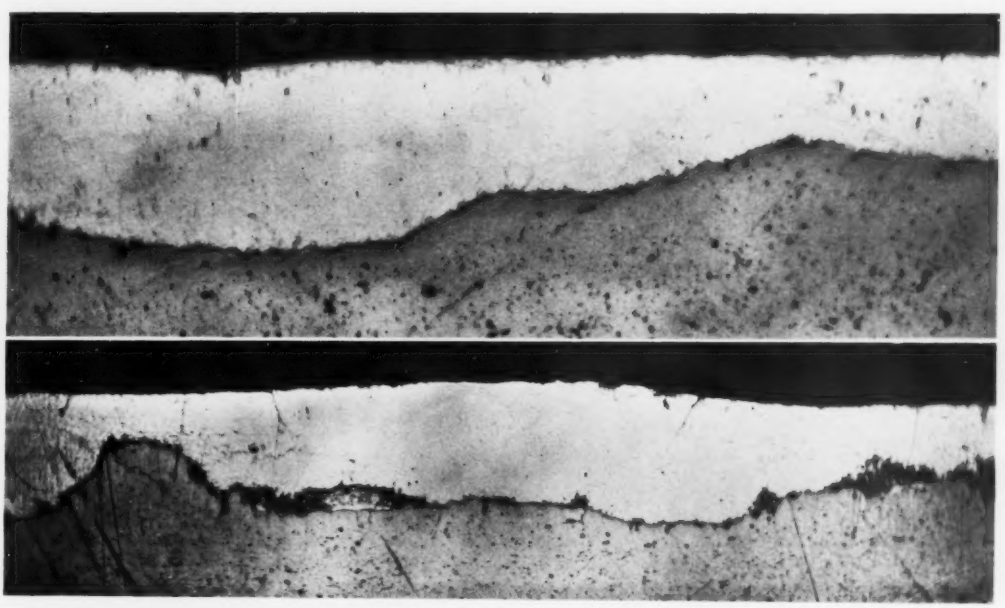
Fig. 7—Sections of coatings on samples of cold reduced sheet steel immersed for 30 sec. and 60 sec. in aluminium-containing baths. Galvanizing temperature 430° C.

(a) 30-sec. immersion in 0·10% aluminium bath showing alloy at crevices only × 1000
(b) 60-sec. immersion in 0·05% aluminium bath × 500
(c) 30-sec. immersion in 0·05% aluminium bath × 1000

Etching reagent for Figs. 6 and 7*a* and *c*, Rowland's No. 3, 0·068 g. of picric acid, 20 ml. of ethyl alcohol, 50 ml. of water. Etching reagent for (*b*), 1% nitric acid in amyl alcohol



(a) (b)



(c)

(d)

Fig. 8—Sections of coatings on samples of pack-rolled steel immersed for 15 and 30 sec. showing good bending properties. Galvanizing temperature 430° C., with aluminium-containing baths

(a) 15 sec. in 0·05% aluminium bath. (Reduced by $\frac{13}{16}$ linear in reproduction)	× 125
(b) 30 sec. in 0·05% aluminium bath. (Reduced by $\frac{13}{16}$ linear in reproduction)	× 125
(c) 15 sec. in 0·10% aluminium bath	× 500
(d) 30 sec. in 0·10% aluminium bath	× 500

Etching reagent 1% nitric acid in amyl alcohol

[*Hughes*

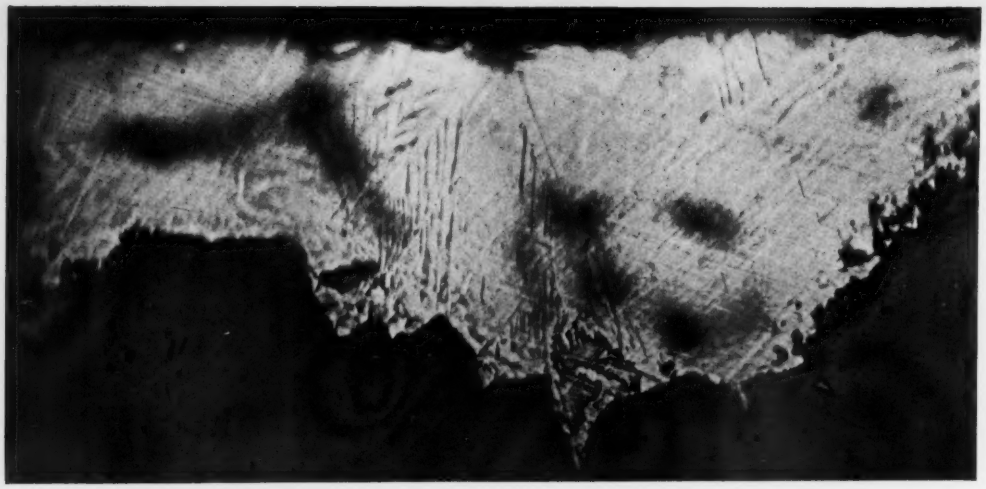
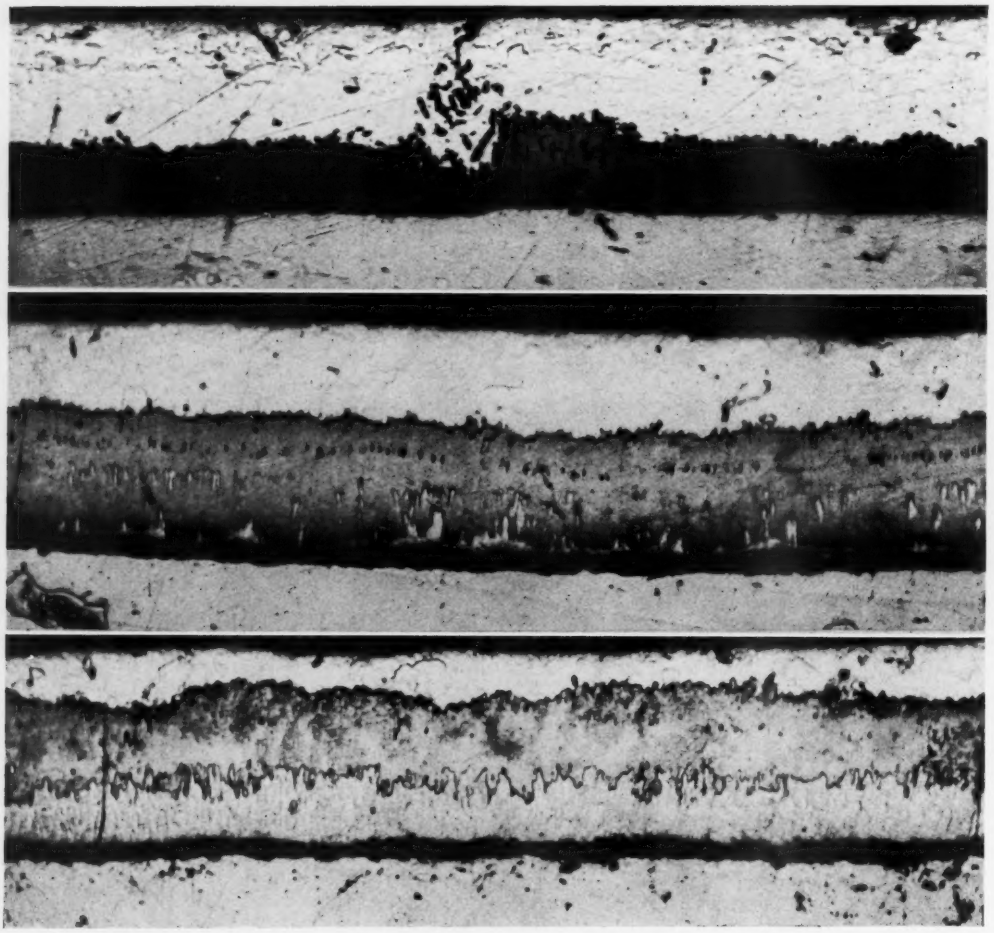


Fig. 9—Section of a coating on a steel surface produced by fracture below the surface of a 0·30% aluminium bath × 500



(a)

(b)

(c)

Fig. 10—Sections of coatings on steel samples galvanized in pure zinc: (*a*) before heating, (*b*) after heating for 1 hr. at 350° C., (*c*) after heating for 30 min. at 375° C. × 500

Etching reagent, Rowland's No. 3, 0·068 g. of picric acid, 20 ml. of ethyl alcohol, 50 ml. of water

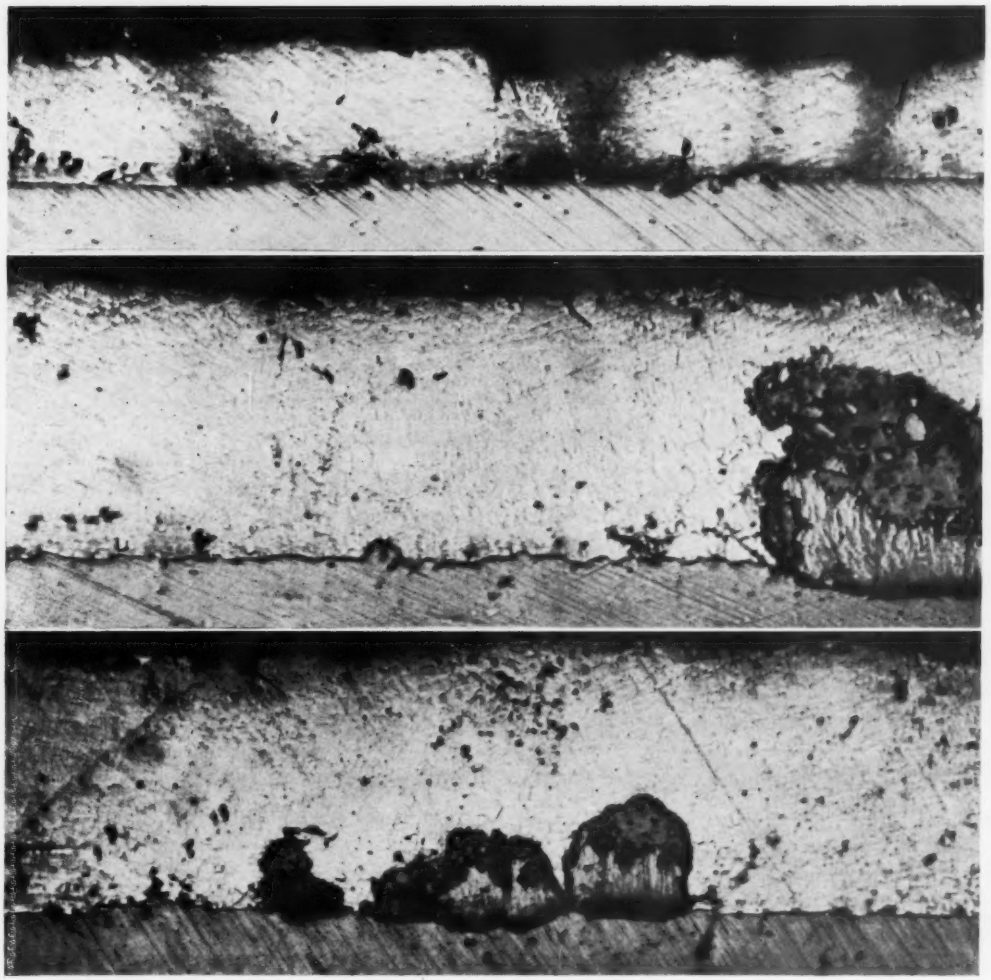


Fig. 11—Sections of coating on steel samples galvanized in 0·3% aluminium bath (*a*) before heating, (*b*) after heating for 1 hr. at 350° C., (*c*) after heating for ½ hr. at 375° C. × 500

Etching reagent, Rowland's No. 3, 0·068 g. of picric acid, 20 ml. of ethyl alcohol, 50 ml. of water

[Hughes

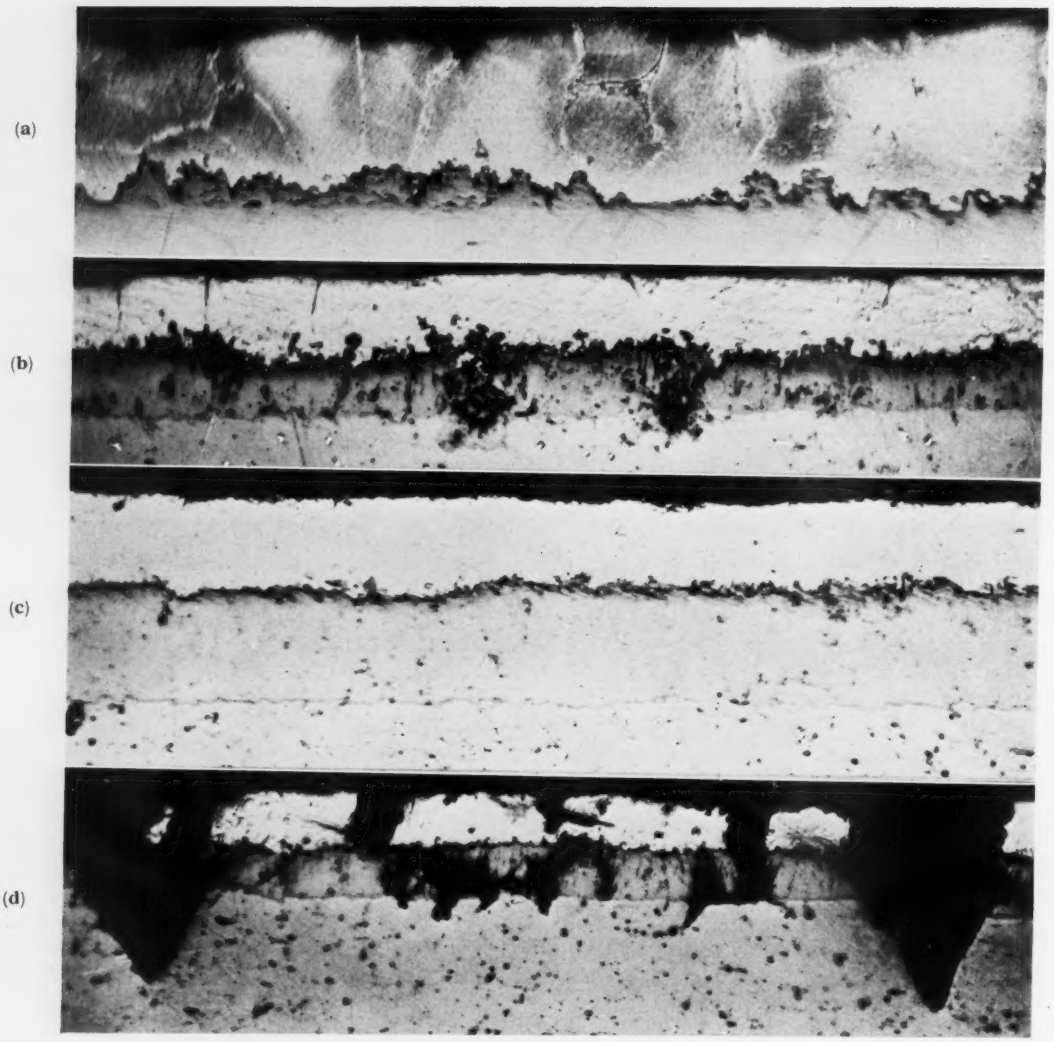


Fig. 12—Sections of coatings on steel samples produced by galvanizing in a 1·5% aluminium bath, showing progressive growth and bending properties of alloy

(a) 30 sec. immersion at 420° C. × 500 (b) 15 sec. immersion at 490° C. × 500
(c) 30 sec. immersion at 490° C. × 500 (d) 30 sec. immersion at 490° C., after alternating bend test × 250

Etching reagent, Rowland's No. 3, 0·068 g. of picric acid, 20 ml. of ethyl alcohol, 50 ml. of water

Hughes]
To face p. 81]

content of 0·2–0·3% is required. At 452° C. the inhibiting action no longer functions. Bablik also records that with high-silicon steel, the effect of aluminium is apparent at 0·05% and is quite marked at 0·10%. The inhibition of alloy formation at 0·04% of aluminium, claimed by Bablik, is not complete, however, according to his photomicrographs. The present author considers that 0·2–0·3% of aluminium is more than is necessary for pure iron, and in his experiments the inhibiting action has not been found to disappear at 452° C.

The surprising results that aluminium, which has a greater affinity for iron than has zinc, and that silicon, which normally increases Fe-Zn alloying to a marked extent, are capable of suppressing or reducing alloy formation, required further study.

Table I shows that an increase in temperature to 490° C. apparently reduces the effect of the aluminium in the bath. By increasing the aluminium addition to 0·33% this effect is counteracted. The three steels *A*, *B*, and *C* were galvanized at 490° C. for 15 sec. and 30 sec. as before, but with 0·33% of aluminium in the zinc bath ; the coatings were essentially alloy-free, except for that on the 0·10% C steel after 30-sec. immersion (*see* Figs. 5*a*, *b*, and *c*). The steel containing silicon is seen to contain much less alloy than the 0·10% C steel.

These results indicate that even in the presence of appreciable amounts of carbon, with or without small amounts of silicon, 0·33% of aluminium can suppress, almost completely, the formation of iron–zinc alloys in hot galvanizing even when the temperature rises to 490° C. Immersion time has been limited to 30 sec. which is ample for sheets or for articles fabricated from sheet. The results obtained by Hall and Kenworthy[9] are not supported ; the effect of rising temperature appears to have been over-emphasized by Bablik. His immersion times are, however, very long.

Hot Galvanizing of Sheet

Ideally, galvanized sheet should be free from flaking. If this can be achieved without complete absence of alloy, the necessary addition might be low enough to permit normal fluxing procedure, possibly with some modification of flux composition. Cold-reduced sheet steel samples have been treated in baths containing 0·10% and 0·05% of aluminium at 430° C. and the results are given in Table II.

Figures 6*a* and *b* show that 0·10% of aluminium can suppress alloy formation at 430° C. even after 30 sec., with complete elimination of flaking in the alternating bend test, even up to the point of rupture of the steel base. Figure 7*a* shows that, after 30 sec., only a little alloy at surface crevices can be seen.

With a further reduction of the aluminium content, down to 0·05%, the usual alloy layers were formed but they were thinner than usual, even after galvanizing for one minute (*see* Fig. 7*b*). The results of bend tests were adversely affected by the unexpectedly thick outer layer. Figure 7*c* shows the result of galvanizing at 430° C. for 30 sec. ; this sample gave excellent bending results, showing no flaking after 22 bends.

The good bending results obtained by adding 0·10% of aluminium, or even 0·05% of aluminium, could be attributed in part to the use of smooth-surfaced cold-reduced steel sheet. Following the suggestion, made more than once, that such material would give better results on galvanizing, a poor quality pack-rolled steel was galvanized for 15 and 30 sec. in baths containing 0·05% and 0·10% of aluminium. The results are shown in Figs. 8*a–d*. Some alloying occurs when the aluminium in the bath is 0·05%, but at 0·10% of aluminium there is no alloy after 15 sec. and very little after 30 sec. Samples galvanized under these four conditions showed good bending qualities. The results with 0·05% of aluminium were sensitive to any abnormal increase in the thickness of the outer layer, since alloy layers are present.

In all the above experiments the samples were prefluxed in a hot solution of zinc–ammonium chloride and partially dried ; this is the practice in all galvanizing carried out in the author's laboratory. The baths were made up from pure zinc. In industrial practice the results obtained by adding a given amount of aluminium would perhaps be affected by the simultaneous presence of lead, tin, and traces of other elements. It is hoped to examine the effect of aluminium additions under actual sheet galvanizing conditions, using a small-scale unit.

Table II

ALLOYING AND BENDING BEHAVIOUR* OF SHEET SAMPLES GALVANIZED IN BATHS CONTAINING 0·10% AND 0·05% OF ALUMINIUM

Steel Base	Galvanizing Temperature 430° C.			
	0·10% of Al		0·05% of Al	
	15 sec.	30 sec.	30 sec.	1 min.
Cold-reduced sheet 26 gauge (smooth surface)	No alloy. No flaking after 22 bends; steel fracturing (*see* Fig. 6*a*)	No alloy. No flaking after 18 bends; steel fractured (*see* Fig. 6*b*)	Appreciable duplex alloy layer. No flaking after 22 bends (*see* Fig. 7*c*)	Thin uniform duplex alloy layer. Outer layer too thick for good bending results (*see* Fig. 7*b*)
	15 sec.	30 sec.	15 sec.	30 sec.
Pack-rolled sheet (rough surface)	No alloy. 11 bends; no flaking; steel fractured (*see* Fig. 8*c*)	Negligible alloy formation. 12 bends; no flaking; steel fractured (*see* Fig. 8*d*)	Very thin alloy layer. 15 bends; no flaking; steel fractured (*see* Fig. 8*a*)	Thin alloy layer. 14 bends; steel fractured (*see* Fig. 8*b*)

* Bending behaviour examined by means of a Jenkins Alternating Bend Tester, using a 0·10-in. bend radius

Mechanism of Alloy Suppression

It has been suggested that alloying is prevented by a membrane, presumably of alumina (*see* p. 78). This theory would explain the local formation of 'clumps' of alloy, but such a film should prove a permanent obstacle to alloying. This is not the case, since a higher temperature and a longer immersion time can overcome the effect of the aluminium. The origin of this film is somewhat obscure ; a film of oxide or moisture on the surface of the sample being dipped, may react perferentially with the aluminium in the melt to form a film of alumina. It has been suggested that the film on the surface of the bath envelopes the steel surface, but this is difficult to accept.

Two experiments suggested by W. C. F. Hessenberg were carried out to ascertain whether an alumina film is formed instantaneously on immersion. In the first, a strip of steel, previously weakened, was bent to and fro while immersed in a bath containing 0·3% of aluminium : when fracture occurred a virgin surface was exposed, free from oxide and of course from moisture. Figure 9 shows that no alloying occurred. In the second experiment the sample was immersed in the bath and its surface then vigorously scraped with a toothed piece of steel to damage the membrane. By the theory, local growths of alloy should be produced ; no such growths were observed.

The author's results in general do not support the theory that the alloy forms but falls away. A piece of sheet steel galvanized in a horizontal position, with a minimum of agitation, galvanized in a 0·3% aluminium bath was found to show no alloy on the under or on the upper face. It is possible that the alloy dropped away from the under face, but it is difficult to explain the complete absence of alloy in the upper coating. This could not fall downwards, and the idea that the presence of aluminium makes it light enough to float upwards[9] is contradicted by other work of the author. Experiments on diffusion in the solid state, described later, also contradict the 'loose alloy' theory.

The remaining theory that the aluminium causes an induction period which slows down the initial rate of alloy formation, has also been investigated. If this theory is true the aluminium should also affect the rate of growth of alloy by diffusion in the solid state. Samples were galvanized in baths of pure zinc and in baths of zinc containing 0·3% of aluminium. The effect of heating these for 1 hr. at 350° C. and ½ hr. at 375° C. is shown in Figs. 10 and 11, the structures before heating being included.

It is seen that alloy growth is delayed by the aluminium in the zinc, and that it develops in the form of nodules or clumps. The latter were not visible in the original structure and are therefore not caused by holes in a protective membrane. They are better explained as being more reactive areas where growth is more rapid when once initiated. Figures 11*b* and *c* show that the upper layer of alloy has what appears to be a duplex structure ; this is not seen in coatings free from aluminium and needs further examination.

EFFECT OF ABNORMAL ALUMINIUM ADDITIONS

Alloy Layer Formation

Micro-examination of galvanized samples shows that the use of galvanizing baths containing aluminium tends to roughen the surface of the steel base. In extreme cases the peaks produced appear to etch differently from the rest of the steel base ; in some cases an inwardly diffusing layer was formed. This layer was not easy to detect and was quite different from the normal zeta and delta layers.

Galvanizing experiments were carried out in baths containing 0·75% and 1·5% of aluminium for increasing immersion times and a clearly visible layer was produced which increased in thickness with increasing time of immersion. Figure 12*a* shows the attack on the steel base with some inward diffusion, and Figs. 12*b* and *c* show progressive growth of this layer at a higher temperature and increasing immersion time. These samples were produced from a bath containing 1·5% of aluminium. Figure 12*d* shows that this alloy layer does not flake away from the steel base on bending as with the normal alloy layers. The sample shown was given 19 alternating bends over a 0·10-in. radius until the steel began to rupture without any sign of flaking.

The regular growth of this layer is quite unlike the alloying of pure molten aluminium and immersed steel ; aluminium diffuses inwards very rapidly and on an extremely irregular front. It is therefore possible that there is simultaneous diffusion of zinc, causing a modification of the behaviour.

The outer portion of the coating was removed by selective anodic dissolution and the alloy was stripped and analysed. The iron content of this layer was considerably higher than in the usual iron–zinc alloys (about 45%) but the ratio of aluminium to zinc appears to vary appreciably. The compositions of samples of the alloy, prepared under various conditions, are given in Table III.

The whole of the alloy layer shown in Fig. 12*c* cannot, however, contain such a high percentage of aluminium since the aluminium content of the whole

Table III

COMPOSITION OF ALLOY LAYER FORMED IN GALVANIZING BATH CONTAINING 1·5% OF ALUMINIUM

%	490° C., 1 min.		460° C., 1 min.					490° C., 1 min.			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Fe	44·6	46·5	44·3	40·0	41·2	43·1	40·5	36·8	41·2	35·0	40·3
Al	29·4	39·8	39·7	37·5	33·5	37·3	39·0	36·9*	33·7	34·8	39·8*
Zn	26·3	11·9	16·9	20·6	26·9	19·6*	21·8	26·3	25·9	30·5	20·9

* By difference

coating is insufficient. Further work is needed to verify this result.

The formation of such an alloy, rich in iron and aluminium, would explain the following two peculiarities which arise when aluminium is used in the galvanizing bath :

(1) Laboratory stripping tests have often shown a surprisingly high loss of iron from the basis metal, although little alloy, if any, had been seen in micro-examination

(2) Analyses of the stripped coating frequently shows it to have a higher aluminium content than that of the galvanizing bath. This may be attributed to the presence, on the surface of the bath, of an aluminium-rich immiscible liquid layer, some of which is drawn out on the article being galvanized.

The formation on the sample, during immersion, of an aluminium-rich alloy layer serves to explain the enrichment of the coating. The enrichment increases with increased time of immersion, owing to greater alloy formation, whereas by the liquid film theory the enrichment should be independent of time of immersion.

Further samples of the alloy layer are being isolated and analysed with a view to correlating composition with galvanizing conditions and structure. Further metallographic work is also in progress, for it appears that under certain conditions a second alloy layer can appear beneath the layer under discussion, *i.e.*, further into the body of the steel. Samples of the alloy have also been examined by electron diffraction and by X-ray in order to determine the composition of this layer.

The appearance, thickness, and bending properties of coatings produced in baths containing appreciable quantities of aluminium are admirable. The coating shown in Fig. 12*d* is equivalent to about 2·9 oz./sq. ft. of sheet, which is far thicker than that on normal galvanized sheet.

Unfortunately, however, there is a possibility that the simultaneous presence of lead in a galvanizing bath would cause the aluminium-rich coating to fail prematurely if exposed to hot water or steam as in cisterns.[39] A number of samples prepared from baths containing lead and varying amount of aluminium, have been undergoing tests in hot water and steam to examine this possibility. 'List' edges immersed in hot water at 84° C. disintegrated, in some cases in less than a week ; other samples have shown quite good initial resistance, being only slightly darker after two months. These tests will, of course, be continued for a much longer period.

CONCLUSIONS

(1) It is confirmed that the addition of 0·18% of aluminium to a galvanizing bath can produce sensibly alloy-free coatings.

(2) An addition of 0·3% of aluminium produces alloy-free coatings on low carbon material even when the temperature is allowed to rise to 490° C. and the time to reach 30 sec. or more.

(3) The presence of 0·10% of silicon in the steel appears to enhance the influence of aluminium provided the temperature of galvanizing is not excessive.

(4) Under sheet galvanizing conditions (15–30 min. immersion at 430° C.) using low carbon rimmed steel, an addition of only 0·10% of aluminium to the galvanizing bath may be sufficient to prevent the formation of the usual alloy layers.

(5) With 0·05% of aluminium, the usual alloy layers are formed but are thinner than when it is absent.

(6) The flaking of the coating on bending is eliminated by a 0·10% aluminium addition. This may also be achieved with 0·05% of aluminium if the outer layer of zinc is fairly thin.

(7) The improved bending results are shown whether the basis steel is smooth cold-reduced sheet or pack-rolled material.

(8) The theory that the action of aluminium is accounted for by the presence of a membrane is not supported.

(9) The theory that alloy-free coatings are caused by the formation, and immediate breakdown, of a non-adherent alloy is also not supported.

(10) The aluminium appears to promote the formation of a ternary Fe–Zn–Al alloy by diffusion inwards into the steel base. The formation of the ternary alloy is not apparent until relatively heavy additions of aluminium are made, but it is probable that with smaller additions enough alloy may be formed to obstruct the usual formation of the normal zeta and delta layers.

Further Work

The behaviour of different steels in galvanizing depends upon their surface condition. For example, the steel containing 0·10% of carbon is characterized by the absence of a rim or of a decarburized surface. The presence of pearlitic areas in the surface suggests that results will differ from those given by a heavily rimmed steel of the same carbon content. The peculiar effect of silicon also needs further investigation. When all the factors have been examined it may be possible to obtain the benefits of aluminium additions to the galvanizing bath without the associated drawbacks which have so far discouraged its use.

Acknowledgments

Valuable assistance with the experimental work has been given by Mr. D. Glan Thomas. The author is indebted to Mr. W. C. F. Hessenberg, Head of the Mechanical Working Division, and Mr. D. Luther Phillips, Head of the Swansea Laboratories of the British Iron and Steel Research Association, for their interest in the progress of this work.

References

1. J. W. Richards : "Manufacture of Galvanized Iron," U.S. Patent 456,204, 1891.
2. A. Forny : *Galvano*, 1935, vol. 35, pp. 26–27.
3. W. Frochlich : *Illustrierte Zeitung für Blechindustrie*, 1935, vol. 64, pp. 1298–1299, 1323–1324.
4. E. A. Matteson : *Iron and Steel Engineer*, 1947, vol. 24, pp. 61–62.
5. G. A. Brayton : *Journal of the American Zinc Institute*, 1936, vol. 17, pp. 87–93.
6. E. R. Thews : British Intelligence Sub-Committee, 1947, F.I.A.T. Report No. 883.
7. H. Bablik : *Métallurgie*, 1947, vol. 79, pp. 23–25.
8. A. Gordet : *Galvano*, 1937, vol. 59, pp. 24–26 ; vol. 60, pp. 20–24.
9. W. L. Hall and L. Kenworthy : *Sheet Metal Industries*, 1947, vol. 24, pp. 741–752, 758.

10. H. BABLIK and F. GOTZL : *Korrosion und Metallschutz*, 1938, vol. 14, pp. 350–353.
11. H. BABLIK : *Zeitschrift für Metall-und-Schmuckwaren-Fabrikation sowie Verchromung*, 1942, vol. 23, pp. 361–362.
12. P. T. GILBERT : Research Report, Association Series No. 708, April 1946, British Non-Ferrous Metals Research Association.
13. A. BURKHARDT : "Zink und Seine Legierungen," Berlin, 1937 : Verlag.
14. E. SCHEIL and H. WURST : *Zeitschrift für Metallkunde*, 1937, vol. 29, p. 228.
15. H. BABLIK : *Korrosion und Metallschutz*, 1940, vol. 16, pp. 203–206.
16. H. BABLIK and F. GOTZL : *Korrosion und Metallschutz*, 1941, vol. 17, p. 128.
17. D. H. ROWLAND : *Transactions of the American Society for Metals*, 1948, vol. 40, pp. 983–1011.
18. W. M. PIERCE : *Iron Age*, 1938, vol. 141, pp. 34–36.
19. W. H. FINKELDEY : *American Society for Testing Materials*, 1926, vol. 26, pt. II, pp. 304–316.
20. B. A. SIROTKIN : *Ural Metallurgy*, 1940, vol. 9, pp. 19–20.
21. G. K. LVOV and T. S. SHLEGOL : *Ural Metallurgy*, 1940, vol. 9, pp. 16–19.
22. ANON : *Metalloberfläche*, 1947, vol. 1, p. 141.
23. ANON : *Electroplating*, 1948, vol. 1, pp. 572–573.
24. H. BABLIK : *Metal Treatment*, 1947, vol. 14, pp. 29–35.
25. E. J. DANIELS : *Journal of the Institute of Metals*, 1931, vol. 2, pp. 81–96.
26. H. BABLIK : "Das Feuerverzinken," Vienna, 1941 : Springer.
27. H. BABLIK : *Metal Industry*, 1946, vol. 68, pp. 487–489.
28. H. BABLIK : *Corrosion and Material Protection*, 1948, vol. 5. pp. 8–9.
29. W. G. IMHOFF : *Metal Finishing*, 1949, vol. 47, pp. 65–75.
30. W. G. IMHOFF : *American Metal Market*, 1937, vol. 44, pp. 3, 5.
31. W. G. IMHOFF : *Metal Cleaning and Finishing*, 1937, vol. 9, pp. 19–20.
32. W. G. IMHOFF : *Metal Cleaning and Finishing*, 1936, vol. 8, pp. 143–146.
33. W. FROHLICH : *Oberflächentechnik*, 1941, vol. 18, pp. 142–143.
34. E. J. GROOM : *Metallurgist*, 1938, vol. 11, pp. 162–164.
35. T. LIBAN : "Methods of Applying Zinc Coatings to Iron Articles," U.K. Patent 257,262, 1927.
36. A. J. MAUGER and A. H. WARD : "Process of Galvanizing," U.S. Patent 2,405,592, 1941.
37. C. E. RICHARDS : *Journal of The Iron and Steel Institute*, 1938, No. I, pp. 127P–176P.
38. H. BABLIK, F. GOTZL and R. KUKACZKA : *Korrosion und Metallschutz*. 1945, vol. 21. pp. 1–8.
39. K. LOHBERG : *Metallforschung*, 1947, vol. 2, pp. 230–232.

The Measurement of Stockline Contours on Driving Blast-Furnaces

By E. W. Voice, B.Sc., A.Inst.P.

CONSIDERABLE attention has been given recently to the influence of distribution of charges on blast-furnace working, but field trials on furnaces to obtain the stockline contours have been made with mechanical methods.[1, 2, 3]

The results of tests at the works of the Appleby-Frodingham Steel Co., Ltd., showed correlation between gas analyses and the anticipated stockline,[4] and more recent experiments on controlled distribution also show a relation between known stockline and gas analyses on an experimental blast-furnace.[5]

This note describes an alternative method of providing a pictorial display of the stockline contour of a driving blast-furnace, using radar techniques instead of the difficult mechanical methods. The technique is to transmit energy by a system of low-velocity radar-type pulses. To obtain the low velocity it was found necessary to use sound waves instead of electromagnetic waves, the system used being known as 'Pulsed Sondar.'

The first equipment used a sparking plug as a generator. Short pulses of sound are directed to the stockline and the reflected echoes are received by a crystal microphone. The time taken is measured and the receiving equipment presents the distance from source to stockline in the form of a continuous record of distance. By moving the transmitter and receiver across the top of the furnace a pictorial presentation of the shape of the stockline across the diameter may be obtained. It should also be possible to have a fixed transmitter and receiver arranged so that they can scan the entire stockline.

The precipitation of dirt from the atmosphere on the electrodes of the sparking plug, was largely prevented by passing a stream of clean air or gas over the electrodes.

Subsequent work has shown that magnetostriction transmitters and receivers may be more suitable than a sparking plug and crystal microphones, for use in a blast-furnace.

Acknowledgment is made to Messrs. G. Bradfield and H. G. Manfield (Ministry of Supply, Telecommunications Research Establishment, Malvern) for the design of the spark transmission and reception equipment. Also to Messrs. D. W. Gillings and H. D. Ward of B.I.S.R.A. for carrying out the practical developments and operational trials.

References

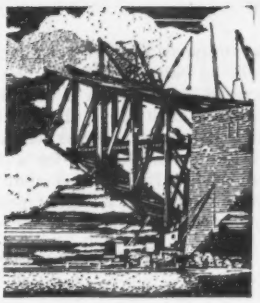
1. H. MAGUIN : *Revue de Métallurgie*, 1938, vol. 35, pp. 531–533.
2. J. M. STAPLETON : *Transactions of the American Institute of Mining and Metallurgical Engineers*, 1943, vol. 154, pp. 62–90 ; *Metals Technology*, 1943, vol. 10, pp. 89–117, Technical publication No. 1541, Jan. 1942.
3. E. W. VOICE : *Journal of The Iron and Steel Institute*, 1949, vol. 162, p. 450.
4. "Reports upon Blast-Furnace Field Tests," *Special Report No.* 18 : 1937, The Iron and Steel Institute.
5. H. L. SAUNDERS, G. B. BUTLER and J. M. TWEEDY : *Journal of The Iron and Steel Institute*, 1949, vol. 163, pp. 173–206.

Manuscript received 17th May, 1950.

Mr. Voice is in the Field Trials Section of the Iron Making Division of the British Iron and Steel Research Association.

IRON AND STEELWORKS ENGINEERING

THE IRON AND STEEL ENGINEERS GROUP



THE IRON AND STEEL ENGINEERS GROUP

REPORT OF THE TWELFTH MEETING

THE TWELFTH MEETING OF THE IRON AND STEEL ENGINEERS GROUP of The Iron and Steel Institute was held at 4 Grosvenor Gardens, London, S.W.1, on Thursday, 23rd March, 1950. Mr. W. F. CARTWRIGHT (Steel Company of Wales, Ltd.), Chairman of the Group, occupied the Chair, except for a short period at the end of the Afternoon Session, when his place was taken by Mr. W. J. POOL.

The MORNING SESSION was devoted to the presentation and discussion of two papers, entitled "Traffic of Iron and Steel Works—A Method of Traffic Analysis," by H. H. MARDON and M. D. BRISBY (B.I.S.R.A.), and "Traffic of Iron and Steel Works: The Application of Very High Frequency Radio Communication," by H. H. MARDON, H. A. CHAPMAN, and M. D. BRISBY (B.I.S.R.A.).

The AFTERNOON SESSION was devoted to the presentation and discussion of two papers, entitled "Structural Frames for Melting Shops," by J. S. TERRINGTON (B.I.S.R.A.), and "A Proposed Method of Specifying Travel Motion Performance for Steelworks Overhead Cranes," by D. A. WISE and L. N. BRAMLEY (B.I.S.R.A.).

PROCEEDINGS OF PART OF THE AFTERNOON SESSION

2.0 P.M. to 4.30 P.M.

Discussion on the Paper—

STRUCTURAL FRAMES FOR MELTING SHOPS*

Mr. **J. S. Terrington** (British Iron and Steel Research Association) introduced his paper.

Mr. **A. P. Clark** (Dorman, Long and Co., Ltd.): In examining the designs, one cannot help but notice, in spite of their wide variety, that the author has a distinct preference for the portal frame, and for plated construction, over the more conventional non-rigid frame and lattice braced construction.

Below crane gantry level there is probably little room for differences of opinion on the merits of lattice braced *versus* plated construction, since very heavy loads must be carried over wide spans by girders with a limited available depth, and be supported by stanchions with a large steel area designed to occupy the minimum of the valuable space available; in particular, adjacent to the furnaces, at the back of the charging stage, and where railways pass from one bay to another.

Above gantry level, whilst clean lines and an air of spaciousness are desirable, it is to be regretted that none of the proposals attempts to incorporate any improvement of the orthodox lattice roof truss.

Built-up plate girders, whether riveted or welded, to form the roof of a building of this size and duty, will almost certainly be found to be more expensive than lattice trusses. They have the added disadvantage that gangways for access to lighting and glazing cannot form an integral part of the structure, as is often possible with lattice braced trusses. The last word on the subject of the lattice roof truss has surely not yet been said, and with care in design and a regard for internal and external appearance, it should be possible to produce a design which is efficient and aesthetically satisfying.

The various designs show several arrangements of glazing, transversely and longitudinally placed, vertical and inclined, but there is no comment on their respective value. Two factors should be borne in mind by a building designer: (i) the general intensity of the light on the working floor, and (ii) the evenness of the light, particularly with reference to the presence of shadows.

* *Journal of The Iron and Steel Institute*, 1950, vol. 164, Feb., pp. 195–222.

A comparison of various methods of providing natural lighting can be made on the drawing board, and in the present paper such a comparison would have been of great interest and value, although it might give results different from those expected. For instance, an investigation made recently for a long, narrow shop, with roof lighting only, showed that longitudinal glazing gave more even, and a higher general level of lighting, than transverse glazing.

Mr. **J. S. Terrington** : I consider that the object of a roof is to follow the envelope, which is the minimum rectangular-shaped shell that can be designed to cover the plant ; the roof construction has then to be put over that. Surely one should not put a mass of lattice roof trusses over it, but should arrange a space frame to follow that envelope as closely as possible. The ordinary lattice roof truss just does not find any place in the scheme of things if one uses a grid type of roof.

The matter of cost has already been dealt with at meetings of the British Welding Research Association, and it is agreed that welding costs are no more than those of riveting. At present they are, in fact, found to be more, because of restrictive practices and other reasons, but, without doubt, these conditions will improve.

I fully endorse Mr. Clark's remarks on natural lighting. It might very well form the subject of a separate investigation.

Mr. **W. S. Atkins** (W. S. Atkins and Partners) : The actual problem in the design of melting shops is generally the crane-bearing structure. It is not a building but it is a piece of the plant, and it should be designed as such. The structural frame is planned to maintain crane alignment and to be subjected to the longitudinal and transverse forces occurring in normal crane use and abuse. Its frames have to deal with those forces with the minimum of maintenance over a long period.

If the actual conditions that are imposed upon these frames are considered the solution will not necessarily be that the frame should be a plate girder or lattice girder—that is just the fancy of the individual designer. The structural frame transmits the crane forces to foundations, and if a continuous frame is used one has to think of the action in the whole of the frame in dealing with those forces.

In my opinion, some of the suggested types I–X in the paper are not the most efficient for the purpose. The open portal-type frame provides a clean outline, but this is not necessarily superior, for the purpose, to a properly designed discontinuous frame comprising cantilever stanchions and roof trusses, which would maintain transverse dimensions, and hence crane-track alignment. Nor is the latter equal to a continuous frame that would fulfil this condition.

Where cranes are lightly worked the open portal-type pitched-roof frame is pleasing and sufficient, but where cranes are heavy and hard-worked, I consider that such frames would allow movement in the roof outline, and hence greater lateral movement at crane level than is necessary or desirable.

One is driven to the type of frame that will consume the minimum amount of metal yet give the rigidity and distribution that is needed effectively to maintain crane-track alignment and so reduce maintenance and wear. For these reasons I disagree with the use of open frames, as illustrated, in melting shops and similar buildings.

Longitudinal framing must be stiff so as to resist longitudinal forces up to crane-rail level, for that is the point of action. Above that level, other stiff lines of framing only confuse the issue. It is better to frame and design up to crane-girder level to deal with longitudinal forces and to allow a certain amount of articulation above that level. The design then becomes very much clearer.

The cost of frameworks must be defined by the conditions to which a frame is subjected, and by the skill of the designer. If it is efficient, it will establish its own cost. As far as welded costs are concerned, we have not found it dearer to use welding than to use riveting—in some cases, in fact, we have found it cheaper.

Mention has been made of natural lighting. We consider that vertical lighting is always the best because it keeps clean. Longitudinal or transverse glazing can both be equally efficient, but some preference may be indicated by the type of building. From the outline of the shop and the reflectivity obtained inside the building, they will define themselves and can be compared theoretically by lighting contours plotted at floor level. Simple transverse lighting sections are not sufficient to give the required variations over the shop floor.

Finally, I suggest that, if it is possible to set down proper rules for the design of crane-bearing structures, it is timely that there should be a link-up between the crane manufacturers and the structural engineers.

Mr. **Terrington** : In view of Mr. Atkins' particularly wide experience at the Abbey Works and elsewhere, on this class of building, I thank him for his interesting remarks, and I endorse much of what he said. On the question of whether the frame as a whole should take part in resisting lateral forces I doubt whether one should rely solely on a fixed base, which he seems to be advocating. This would be a return to the old form of construction.

Mr. **Atkins** : I am not necessarily advocating stiffness at the base, because the degree of base rigidity is defined by the site conditions. What I said was that the frame, whatever type is used, eventually has to transmit the imposed loads to the foundations.

Mr. **W. J. Storey** (Colvilles, Ltd.) : This paper has been wholly concentrated on the use of framed structures, fixed, portal, and rigid. I consider that attention should be given to the simpler structure that gives greater flexibility in manufacture, erection, and if needed, later modification.

For rapid manufacture the spread of the fabrication over more machines and many shops can readily be achieved with the theoretically pin-jointed structures so widely used today. For rapid erection, in tune with plant progress, the flexibility to be gained from independent structures will be obvious. Our experience has shown that changes in furnace design, charging methods, and casting practice usually require the removal, modification, or re-siting of main structural members ; framed structures do not easily lend themselves to such treatment.

Most of the author's suggested designs refer to the building of a melting shop on a clear site, yet the steel trade has many problems arising from treatment of existing buildings, extensions to existing buildings, and the erection of new plants on sites already partly used in day-to-day production. I feel that some additional ideas on this subject would have been a real contribution.

I realize, however, that much work has already been done on the study of existing designs and the weaknesses of crane gantry girders, as a continuation of the present investigation. There will be some evidence of that work fairly soon, which will be a great help to everyone concerned. It is evident that the crane designers and the structural engineers must be linked more closely in the treatment of this problem.

We consider that welded construction will be pre-

eminent in the future development of crane girders, and fortunately most structural firms are laying out their manufacturing processes to that end. The use of high-tensile steel can be economically applied. At the present stage of development, however, structural firms are not able to make welded frames of the solid web type, as distinct from crane girders, as cheaply as the more orthodox lattice frame.

I hesitate to suggest that all crane girders should be continuous since many changes in furnace construction take place below ground level. I have seen stanchions undermined for special purposes, and the slightest slip would have upset completely the girder continuity.

The roof of these buildings is, I agree, simply an umbrella, and I disagree with Mr. Atkins' view that the roof should form part of the crane structure. Roofs should be kept as low as possible, and the glazing as near vertical as possible. I think the answer is a mansard outline.

The possibility of corrosion has been a strong argument against the simple framed roof trusses and the like, yet in the older shops there has been no evidence of roof members affected by corrosion—the base of the stanchions is a more likely point. I am inclined to discount corrosion as a design factor so long as a reasonable minimum thickness is used.

In stanchion design for the future, I believe that we should not rely on a theoretically fixed end. Whilst stanchions should go deep enough to clear any flue or furnace construction, they should be large enough to transmit all loads to the foundation without high eccentricity. The stanchion shafts should be free from all the bits and pieces of bracing and battening; the heavy plain surface is the ideal type.

Ventilation has not been considered sufficiently. The longitudinal jack-roof ventilator seems to have been accepted in the past and never really proved, although I have seen figures showing that the side wind on such a ventilator goes right through to the other side without extracting the fumes from the building. It has been found, particularly on the lee side of a building (where one can expect a prevailing wind to really prevail) that to aid both lighting and ventilation the 'space sheet' has much to recommend it. In recent extensions we have made they produce an ideal shop.

Mr. **Terrington**: In regard to roof-truss alterations, in spite of the unconventional nature of the designs put forward, I consider that they can be adapted if necessary, in an emergency, and that the ordinary roof truss is not necessarily the only answer to rapid alteration.

On the question of design it should be placed on record that both design and construction of rigid frames are somewhat complicated, and at present few offices are equipped to deal with the design, and few contractors are equipped to deal with fabrication and construction. To some extent, therefore, it is a matter of pioneering the ideas generally, and it is with that object that the paper has been written.

Mr. Storey referred to continuity. I can assure him that continuity provides a reserve of strength; a reserve which has been proved by Professor Baker in his researches that resulted in the Morrison shelter. Bridges on the continent were found to be much more difficult to blow up if they were continuous than if they were freely supported.

Mr. **O. Bondy** (London): One of the author's main difficulties in preparing such an admirable survey was that of stating in clear terms what were the results of comparison of the many types of possible solution for the same problem. I feel that there never will be one solution for one problem only, and that the many different factors and different conditions of site, subsoil, wind, crane loads, and so on, will decide ultimately which of the many alternatives will be the most economical solution.

I agree that the survey is valuable and stimulating in many ways, because it will provide the future designer with pictures of certain types of structure which he may never have thought of in his preliminary investigations. It should be clearly emphasized, however, that rigid-frame portal construction has definitely come to stay.

Regarding the cost of the steelwork, it is easily overlooked that the steelwork itself is only a part—sometimes even a small part—of the total cost. In one case, a factory building to my design, the portal type was found to be about 10% heavier in weight of steel. Fortunately the clients realized from the beginning that the total cost was to be taken into account. This was found to be much smaller for the rigid portal-frame type than for the orthodox lattice roof truss. The question of welding or riveting did not arise, because the advantages of welding were too obvious to be discussed. I believe some firms are very well equipped to do excellent welded jobs at even lower costs than for riveted work, and I see no reason why a welded rigid portal frame should not be cheaper per ton than a riveted portal frame. Fortunately, we have certain figures, not only from the Continent but also from Britain, that confirm this view.

The author makes clear, on page 206, that he wants ample rigidity to keep crane tracks in good alignment. I should like to ask him what is ample rigidity? Are there any limits available, or is this point just being covered by those requirements of the crane makers which we all hope will be published soon? It would be much easier for the structural designer to know that he has to limit the lateral deflection to a definite fraction of the span. After all, such limits for floor beams, purlins, and so on, have been specified in British Standard Codes of Practice, and I think it ought to be possible to provide similar figures for crane tracks.

On page 207 the author claims that the mathematical computations for rigid-frame structures are complex. That is so, but this should not frighten us from tackling such a job. Rigid-frame structures can be designed without much waste of time, and they often introduce new ideas that help to produce a more satisfactory structure.

About twenty years ago nobody seemed to think that the appearance of a steelworks shop mattered. Now, I am glad to say, the aesthetic appearance of the completed job does matter. This is all to the good and need not necessarily mean heavier steelwork or increased cost.

Mr. **Terrington**: I do not know that I have a special figure in mind, in regard to ample rigidity, but probably Mr. Atkins can give us more up-to-date information on that subject, in view of his experience at the Abbey Works.

Mr. **Atkins**: I can only think of limiting it to the clearance between the crane wheel flanges and the width of rail. It is not possible to take up that total amount, and the limit would be about half. This may well be excessive.

Mr. **Terrington**: I believe the vertical deflection is about 1–1½ in. on a 120-ft. girder; but I have no information about lateral rigidity. The play of the crane wheels, or half of that, would no doubt be a very suitable figure.

CORRESPONDENCE

Mr. **J. L. Gaskell** (Appleby-Frodingham Steel Company) wrote : The author mentions the poor standard of natural and artificial lighting in most existing melting shops and the need for considerable improvement. Whilst some attention has been given in the paper to access for maintenance of natural lighting it would appear that no attention has been given to access to the artificial lighting installation. It is of fundamental importance to the maintenance of a good standard of artificial illumination that full access should be available, independent of the overhead cranes. I suggest that maintenance of artificial lighting from overhead cranes is acceptable only for those locations where the cranes are not in continuous use, *e.g.*, a power house, and even then the operation is a hazardous one.

The triangulated roof truss has the advantage, from the lighting engineer's point of view, that catwalks can be simply arranged to give continuous access to a technically good installation. The portal-frame construction involves difficulties in this direction since underslung catwalks would doubtless be held to spoil the lines of the building. Whilst in some of the suggested designs the window-cleaning cradles would provide access to a reasonable artificial lighting installation, most of those shown would require additional facilities.

It is advisable to stagger lighting fittings across a bay to minimize the blocking of the lights by the overhead cranes, but this staggering is difficult to arrange with the transverse portal-frame type of construction.

The author states (page 202) that lighting points cannot be suspended low enough to provide a useful intensity on the stage or floor ; but this is merely a matter of correct choice of fittings for the mounting height. Furthermore, a low mounting height for lighting fittings in a lofty building would result in a dark overhead tunnel, which is considered to be psychologically undesirable.

Mr. **Roosevelt Griffiths** (University College, Swansea) wrote : Building frameworks in the past were erected at a minimum cost, and there is little doubt that this will apply in the future except, possibly, in large firms. There is a marked preference by certain firms for a particular form of structure.

Welded structures will no doubt be widely used in the future, but it remains to be seen whether they will stand up to the overloading and maltreatment that steelworks buildings receive in the course of time. These shocks are unpredictable and are often the result of the lack of common sense on the part of the workman. For example, one would not expect a main roof column to be regularly used as a means whereby the skull from a large ladle is detached by striking the ladle against the column. But such was regular practice, and the column was fractured in several places as well as distorted as a result of this treatment. There is a serious need to devise means of protecting columns from damage from magnet cranes, charger arms, and other moving equipment. In this connection the 3-ft. clearance for the charger arm shown in Fig. 8 appears to be inadequate.

The painting of a portal frame is less costly than the painting of roof principals, but against this should be set the extra labour costs in handling and erecting a scaffolding for a portal frame.

Lighting from windows is seldom satisfactory. The iron-laden dust, carried upward by hot air currents, causes rapid discolouration of the glass, that is difficult to remove. Continuous cleaning is necessary, but is not practised. Ventilation is largely influenced by the psychology of the furnace men, who are not satisfied that ventilation is sufficient unless they can see roof openings. From this aspect the cheapest and probably the most efficient ventilators are the centrally pivoted swing type. Entry of normal rainfall is prevented by the upward current of warm air.

Louvres to the ventilators on portal-type buildings are shown in the paper, but in the writer's experience these have never been found satisfactory on works buildings.

No good designer would drain the roof surface water near the furnaces.

It is doubtful if the sizes of buildings can be standardized in view of different opinions as to the best size and the varying site conditions. A very large shop has an adverse influence on the workman's well-being : it dwarfs his personality, and there is probably an optimum size which provides spaciousness without being overpowering.

REPLY TO CORRESPONDENCE

Mr. **Terrington** wrote in reply : Mr. Gaskell's observations are appreciated and understood, but I believe that there is still scope for originality in designing suitable alternative methods of lighting to suit space-frame construction, rather than adhering slavishly to existing practice.

The practical points to which Mr. Roosevelt Griffiths has drawn attention are particularly useful, and should, I agree, be borne in mind when arriving at a final design.

Detection of Carbon Monoxide Gas

Dangerous concentrations of carbon monoxide may occur in many industries, particularly steelworks, foundries, gas works, coke-oven plant, and wherever gas producers and water gas plant are used. It is most dangerous when formed unknowingly by the improper use of geysers, boilers, and braziers ; in mine explosions (after damp) ; in the smoke from fires ; and in the exhaust gases from internal combustion engines.

A leaflet " Carbon Monoxide," No. 7 in the D.S.I.R. series " Methods for the Detection of Toxic Gases in Industry," has been completely revised and now describes a new, simpler, and more accurate method of detection developed during the war at the Royal Aircraft Establishment.

In the new test a sample of air is drawn through an indicator tube which is stained by the carbon monoxide. The length of the stain gives the concentration present in the air. Complete instructions for carrying out the test are given in the leaflet which is published by H.M.S.O., price 6*d*. (15 cents U.S.A.), by post 7*d*.

Welding Research

A report on " Recommendations for the Metal-Arc Welding of Butt Welds in Steel Pipelines for Power Plant " was published in " Welding Research," vol. 4, No. 3, June 1950. The recommendations cover the butt welding, by the metal-arc process, of steel pipelines of wall thickness from 8 S.W.G. and of diameters exceeding 2 in. O.D. By the methods recommended, pipelines varying from these limits up to 13 in. O.D. and wall thicknesses reaching $1\frac{3}{4}$ in. have been successfully constructed for working pressures up to 2000 lb./sq. in. and working temperatures of 540° C. (1000° F.). The parent materials considered include mild and medium carbon steels ; molybdenum, chrome–molybdenum, and molybdenum–vanadium alloy steels to certain defined specification.

N E W S

ANNOUNCEMENTS AND NEWS OF SCIENCE AND INDUSTRY

THE IRON AND STEEL INSTITUTE

Changes on the Council

Prof. J. H. ANDREW has been nominated to be a Vice-President.

Mr. E. F. LAW has been nominated to be an Honorary Vice-President.

Mr. G. H. JOHNSON (Kettering Iron and Coal Co., Ltd.) and Sir CHARLES BRUCE-GARDNER, Bt. (Messrs. John Lysaght, Ltd.) have been elected Members of Council.

Capt. H. J. THOMAS, President of the Swansea and District Metallurgical Society, has agreed to serve as an Honorary Member of Council during his period of office, to succeed the late Mr. Roosevelt Griffiths.

Special Meeting in Glasgow, 1950

At the invitation of the West of Scotland Iron and Steel Institute, a Special Meeting will be held in Glasgow from 12th September to 15th September. The programme for the Meeting was given in the August issue of the *Journal*. A Paper on "The Production of Steel Plates in Scotland," by J. A. Kilby, published in this issue of the *Journal*, will not be formally presented or discussed.

Symposium on High-Temperature Steels and Alloys for Gas Turbines

The following is a list of the papers to be presented and discussed at the Symposium on High-Temperature Steels and Alloys for Gas Turbines, which will be held in the Lecture Theatre of The Institution of Civil Engineers, Great George Street, London, S.W.1, on Wednesday and Thursday, 18th and 19th October, 1950.

I—Introduction

N. P. ALLEN : "A Survey of the Development of Creep-Resisting Alloys"

II—User Aspects

A. T. BOWDEN and W. HRYNISZAK : "Materials and Performance"

J. BUCHER : "Gas-Turbine Performance and Materials"

S. L. BRAGG : "Influence of Operating Temperature on the Design and Performance of Gas Turbines"

R. W. BAILEY : "Stresses in Gas-Turbine Discs and Rotors"

III—Supplier Aspects

L. B. PFEIL, N. P. ALLEN, and C. G. CONWAY : "Nickel–Chromium–Titanium Alloys of the Nimonic 80 Type"

D. A. OLIVER and G. T. HARRIS : "Some Proven Gas-Turbine Steels and Related Developments"

G. T. HARRIS and W. H. BAILEY : "Effect of Warm-Working on an Austenitic Steel (*G18B*)"

G. T. HARRIS and H. C. CHILD : "Development of a High-Temperature Alloy for Gas-Turbine Rotor Blades"

H. W. KIRKBY and C. SYKES : "Properties of Materials for Gas Turbines"

H. W. KIRKBY and C. SYKES : "Study of the Properties of a Chromium–Nickel–Niobium Austenitic Steel"

E. W. COLBECK and J. R. RAIT : "Creep-Resisting Ferritic Steels"

H. H. BURTON, J. E. RUSSELL, and D. V. WALKER : "Ferritic Steels for Gas Turbines"

W. E. BARDGETT and G. R. BOLSOVER : "Special Steels for Gas Turbines"

IV—Performance Aspects : Scaling and Fatigue at Elevated Temperatures

A. PREECE : "Scaling of Gas-Turbine Alloys"

C. SYKES and H. T. SHIRLEY : "Scaling of Heat-Resisting Steels : Influence of Combustible Sulphur and Oil-Fuel Ash Constituents"

H. J. TAPSELL : "Fatigue at High Temperatures"

P. H. FRITH : "Fatigue Tests at Elevated Temperatures"

H. E. GRESHAM and B. HALL : "Hot Fatigue Testing"

G. T. HARRIS and M. T. WATKINS : "Variation of Elastic Moduli with Temperature for Various Steels and Pure Metals"

V—Special Casting Techniques

A. E. THORNTON and J. I. MORLEY : "Centrispun High Alloy Steel Aero-Engine Components : Part I—The Centrispinning Process ; Part II—Physical and Mechanical Properties of Centrispun Die Castings"

J. TAYLOR and D. H. ARMITAGE : "Centrifugal Steel Castings for Gas Turbines"

H. E. GRESHAM and A. DUNLOP : "Investment Casting of Nozzle Guide Vanes"

E. R. GADD : "Precision Casting of Turbine Blades"

VI—Welding and Machinability Aspects

H. E. LARDGE : "Welding of Heat-Resistant Alloys in Sheet Form"

E. BISHOP and W. H. BAILEY : "Weld-Metal Properties and Welding Characteristics of Two Austenitic Steels Used for Gas-Turbine Rotors"

K. J. B. WOLFE and P. SPEAR : "Machining Austenitic and Ferritic Gas-Turbine Steels"

VII—Special Blade Materials

E. A. G. LIDDIARD and A. H. SULLY : "Chromium-Base Alloys for Gas-Turbine Applications"

J. C. CHASTON and F. C. CHILD : "Some Cobalt-Rich Alloys for High-Temperature Service"

H. J. GOLDSCHMIDT : "Phase Diagrams of the Ternary Systems Fe–Cr–W and Fe–Cr–Mo at Low Temperatures"

R. W. A. BUSWELL, W. R. PITKIN, and I. JENKINS : Sintered Alloys for High-Temperature Service in Gas Turbines"

A. L. ROBERTS and T. G. CARRUTHERS : "Ceramic Materials for Gas-Turbine Blades"

L. ROTHERHAM, W. WATT, J. P. ROBERTS, and F. J. BRADSHAW : "Ceramics for Gas Turbines"

P. GROOTENHUIS and N. P. W. MOORE : "Sweat-Cooling : Review of Present Knowledge and its Application to the Gas Turbine"

VIII—Research and Future Needs

C. A. BRISTOW and H. SUTTON : " Research and Development on High-Temperature Materials "

J. M. ROBERTSON : " Future Needs in Materials for Land and Marine Gas Turbines "

Autumn General Meeting, 1950

The Autumn General Meeting will be held in London on Wednesday and Thursday, 15th and 16th November, 1950.

Meetings in 1951

Annual General Meeting

The Annual General Meeting of the Institute will be held in London on Wednesday and Thursday, 30th–31st May, 1951. A Dinner for those taking part in the Meeting will be held at the Dorchester Hotel on Wednesday evening, 30th May.

Special Meeting in Austria

The Council have accepted an invitation of the Austrian Iron and Steel Institute (Technisch-wissenschaftlicher Verein Eisenhütte Oesterreich) to hold a Special Meeting in Austria during early September, 1951. The Meeting will be held in conjunction with the proposed meeting of the Institute of Metals in Italy during the second half of the month.

Autumn General Meeting

The Autumn General Meeting of the Institute will be held on Wednesday and Thursday, 14th and 15th November, 1951.

NEWS OF MEMBERS

▶ Mr. W. A. ADAM has left Messrs. John Summers and Sons, Ltd., Shotton, Nr. Chester.

▶ Prof. J. H. ANDREW, a Vice-President of the Institute, is retiring from the Chair of Metallurgy, at Sheffield University, on 30th September, 1950.

▶ Dr. W. F. CHUBB has been appointed Foundation Professor of Metallurgy at King Fouad 1st University, Cairo, and will also act as Consulting Metallurgist to the Egyptian Government. Dr. Chubb has had considerable experience with various metallurgical organizations. His educational and research experience has been gained at London University, at the Central Technical College, Birmingham, and at the National University of Eire.

▶ Mr. J. G. COLVIN has been awarded the B.Sc. degree (Metallurgy) of the University of Leeds and has joined the staff of Messrs. Stewarts and Lloyds, Ltd., Corby.

▶ Mr. J. A. EVANS has been awarded the B.Met. degree of the University of Sheffield.

▶ Mr. I. L. GWYNN has been appointed Works Manager at P. I. Castings (Altrincham), Ltd., Cheshire.

▶ Lt.-Col. J. P. HUNT, Managing Director of The Hallamshire Steel and File Co., Ltd., Sheffield, has been appointed Chairman of the National Association of Rolled and Re-Rolled Steel Products.

▶ Mr. F. R. HUTCHINGS has left Messrs. W. H. Allen, Sons and Co., Ltd., Bedford, to take up an appointment in the Research Department of the British Engine Boiler and Electrical Insurance Co., Manchester.

▶ Sir ANDREW MCCANCE, F.R.S., Past-President of the Institute, has been elected President of the British Iron and Steel Research Association in succession to Mr. G. H. Latham.

▶ Mr. R. MATHER, of the Skinningrove Iron Co., Ltd., has been appointed Chairman of the Council of the British Iron and Steel Research Association in succession to Sir Andrew McCance, F.R.S.

▶ Mr. F. H. POOLE, Works Manager of Messrs. Eva Brothers, Ltd., Manchester, has been appointed to the Board of Directors of the Company. He will remain Works Manager.

▶ Mr. K. RAY has been appointed Director of Inspection at the India Store Department, London.

▶ Mr. S. T. ROBSON, London Manager of Messrs. Head, Wrightson and Co., Ltd., has been appointed a Director of the Company.

▶ Mr. A. ROEBUCK has retired from the Board of Directors of Messrs. Hadfields, Ltd., Sheffield. He remains a consultant to the firm.

▶ Mr. W. SORBY has left Messrs. Turton Brothers and Mathews, Ltd., to take up an appointment as Senior Metallurgist in charge of the Research Department of the English Steel Corporation, Ltd., Openshaw, Manchester.

▶ Mr. C. R. TOTTLE has resigned his post as Lecturer in Metallurgy, University of Durham, to take charge of the Metallurgical Laboratories at the Springfield factory of the Atomic Energy Division of the Ministry of Supply.

▶ Mr. A. H. WAINE has been appointed a Director of Messrs. Hadfields, Ltd., Sheffield.

Obituary

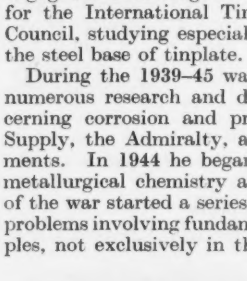
Mr. H. G. DARLING, Chairman of Directors, The Broken Hill Proprietary Co., Ltd., and Australia Iron and Steel Ltd., on 26th January, 1950.

Mr. D. E. ROBERTS, Past-President of the Institution of Mechanical Engineers, on 21st July, 1950.

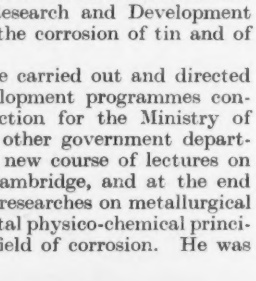
CONTRIBUTORS TO THE JOURNAL

T. P. Hoar, Ph.D. received his early education at Sir Joseph Williamson's Mathematical School, Rochester, and went up to Cambridge University as an Open Scholar of Sidney Sussex College in 1926. After graduating in the Natural Sciences Tripos (Part II Chemistry) and beginning metallurgical research with an equilibrium diagram investigation, he became a research student with Dr. Ulick Evans in 1930, studying the mechanism of metallic corrosion, for which work he gained the Ph.D. degree in 1933. For the next six years he was engaged at Cambridge in corrosion and related researches for the International Tin Research and Development Council, studying especially the corrosion of tin and of the steel base of tinplate.

During the 1939–45 war he carried out and directed numerous research and development programmes concerning corrosion and protection for the Ministry of Supply, the Admiralty, and other government departments. In 1944 he began a new course of lectures on metallurgical chemistry at Cambridge, and at the end of the war started a series of researches on metallurgical problems involving fundamental physico-chemical principles, not exclusively in the field of corrosion. He was



T. P. Hoar



D. V. Atterton

I. M. Mackenzie

Mrs. A. J. Donald

appointed University Lecturer, his present position, in 1946.

D. V. Atterton, B.A.—Research Student, Department of Metallurgy, Cambridge. Mr. Atterton was educated at King's School, Rochester, and at Bishop Wordsworth School, Salisbury. He entered Peterhouse, Cambridge University, in 1944, where he read Parts I and II of the Natural Science Tripos. In 1947 he was awarded the B.A. degree (1st class honours in Metallurgy) and was elected a College Bachelor Scholar. In the same year he started research work under Dr. T. P. Hoar and is at present engaged in research on the surface tension of molten metals.

Ian M. Mackenzie, B.Sc.—Member of the Research Staff of Messrs. Colvilles, Ltd. Mr. Mackenzie received his technical education at The Royal Technical College, Glasgow, graduating with honours in 1945. He has been engaged in research on problems relating to the production of steel ingots. He is a member of the Gases and Non-Metallics Sub-Committee of the British Iron and Steel Research Association. Mr. Mackenzie has published a paper on the determination of the oxygen content of liquid steel and has collaborated in papers on the statistical investigation of ingot surface defects and the development of high-tensile structural steels. He joined the Research Staff of Messrs. Colvilles, Ltd., in 1945.

Andrée J. Donald—Statistician in the Research Department of Messrs. Colvilles, Ltd. Mrs. Donald was born at Soucieu-en-Jarret in the South of France. She received her education at the Ecole Normale Supérieure de Fontenay-aux-Roses, specializing in mathematics, and subsequently became a Lecturer in mathematics at Ecole Normale de Mende, and later in Moulins. She escaped from France to North Africa in 1940, and came to Scotland with her husband in 1944. She was appointed to her present position in 1946.

BRITISH IRON AND STEEL RESEARCH ASSOCIATION

Research Colloquia

A series of research colloquia was held during June and July in which the work of the five sections of the Physics Department was discussed. The Heat and Thermodynamics Section was engaged mainly on flame radiation research, which formed part of the international project centred at the Royal Dutch Steelworks, Ijmuiden. Calculation of the results of the first block of engineering trials has shown clear effects on flame radiation for each of the five variables studied, and two methods have been applied for deducing flame temperature and emissivities. Apparatus is now being assembled for a detailed investigation of processes within the flame. Other subjects discussed were the measurement of temperature in steelworks practice, covering liquid steel, steel surface, and gas temperature measurement.

The progress of the research on the continuous casting of steel was described by the General Physics Section. Many successful laboratory casts had been made and the effects of casting speed and liquid steel temperature on the character of the bar produced have been investigated. Measurements were being made on heat transfer through the mould, and on the friction between the ingot and the mould during continuous casting. The accuracy and range of application of X-ray fluorescent analysis of alloy steels was being examined. Nickel and chromium could be estimated by this method and other alloying elements were being considered.

Model studies of the furnace had been applied by the Aerodynamics Section to such problems as roof erosion and the mixing of air and fuel. The difficulties of measuring gas velocity at high temperatures were described. Pitôt tubes had limitations for this purpose and alternative methods were under consideration.

A reference was made by the Instruments Section to further development work on the wire-drawing die profilometer,* which was directed towards increasing the operating speed of the instrument. The autocollimator had now been replaced by a photo-electric cell, amplifier, and servo motor, which automatically adjusted the micrometer screw to balance. By means of a two-coordinate plotting table coupled to the instrument, the die profile could be continuously traced to an accuracy of 0·00025 in. within 3 min.

A large part of the work of the Mathematics Section had been devoted to a statistical analysis of the results of flame radiation trials in Holland. Data on American open-hearth furnace practice were also being collected and analysed. The results of trials on the use of Xonakry ore in blast-furnaces were also being analysed.

The next series of colloquia will be held in December and visitors from steelworks who are interested in the work of any of the sections will be welcome to take part in the discussions. J. S.

Junior Steelmaking Conference

The 4th Junior Steelmaking Conference was held at Ashorne Hill on 21st and 22nd June, 1950. A feature of the Conference was the use of the discussion-group technique during the Wednesday evening session, which was devoted to the subject of "Refractories: The Building and Maintenance of Open-Hearth Furnaces," the speaker being Mr. J. Pluck (Steel, Peech and Tozer). After Mr. Pluck's talk, in place of the usual open discussion, the members, in previously constituted groups of eight, assembled in separate discussion rooms to consider questions on the subject which were put to them by the Chairman, Mr. W. Geary (Appleby-Frodingham).

The following morning, Mr. Brandt spoke on "The Application of Oxygen in Steelmaking" which gave rise to a lively discussion.

Later, a Brains Trust was held under the Chairmanship of Mr. Robinson. Some of the questions submitted by the members were of a highly controversial nature and on the whole the Brains Trust put up a creditable performance.

Committee Changes

The former Foundry Moulding Materials and Refractories Committee (SC/C) is now called the Foundry Moulding Materials Committee, a separate Committee (SC/D) having been formed to deal with Foundry Refractories. The Sub-Committee (SC/CA) on Side-Blown Converter Refractories, is absorbed in the new Committee.

* R. M. J. Withers, *Journal of The Iron and Steel Institute*, 1950, vol. 164, Jan., pp. 63–66.

A chart of the Committee organization of B.I.S.R.A. was published on p. 326 of the March, 1950, issue of the *Journal*.

NEWS OF SCIENCE AND INDUSTRY

Fatigue and Fracture of Metals

The proceedings of the Conference on the Fatigue and Fracture of Metals, organized by the Massachusetts Institute of Technology, from 19th to 22nd June, 1950, will be published by the Technology Press during the next few months. In addition, brief abstracts of certain papers are available from Professor William M. Murray, Secretary of the Conference, Room 3-257, Massachusetts Institute of Technology, Cambridge 39, Massachusetts.

Scientific Method in Industrial Production

The Industrial Applications Section of the Royal Statistical Society is organizing a Conference on Scientific Method in Industrial Production, at Sheffield University, from 29th September to 1st October, 1950. The conference will be of general interest to technologists. Technicians and managements of manufacturing concerns will be able to meet statisticians interested in industrial problems.

Applications to attend the conference, and further particulars may be obtained from the Assistant Secretary, The Royal Statistical Society, 4 Portugal Street, London, W.C.2.

Study and Utilization of Slags

The Belgian Association for the Study of Glass and Silicon-containing Materials has organized an international conference on the study and utilization of slags, to be held in Brussels from 23rd to 25th October, 1950. Papers on the production, properties, and uses of slags will be presented. The subjects to be covered will include the physical chemistry of slags, the metallurgy of ferrous and non-ferrous slags, and their use in the building industry and in glassworks.

Manchester Fuel Efficiency Exhibition

The Minister of Fuel and Power, Mr. Philip Noel-Baker, has accepted, subject to Parliamentary duties, an invitation to open the "Fuel Efficiency in Industry and Home" Exhibition to be held at the City Hall, Manchester, from 22nd November to 2nd December, 1950.

The exhibition, which is being held under the auspices of the National Smoke Abatement Society, will feature plant and appliances that promote the better and more economical use of fuel of every kind, and is being planned to give full prominence to both the industrial and the domestic aspects. It will be the first comprehensive exhibition of its kind to be held since the war.

Changes of Address

BRITISH SCIENTIFIC INSTRUMENT RESEARCH ASSOCIATION have removed their Library and Information Department to their Laboratories at Chislehurst. The new address is:

The Information Department, B.S.I.R.A., 'Sira,' Southill, Elmstead Woods, Chislehurst, Kent. (Tel: IMPerial 2237.)

THE S.T.A. DEPARTMENT OF THE SHELL PETROLEUM CO., LTD., has removed from Norman House, Strand, W.C.2, to P.O. Box 83, Shell Court, White Kennett Street, Houndsditch, London, E.1. (Tel.: Avenue 7575.)

BORAX CONSOLIDATED, LTD., have returned to their pre-war offices at Regis House, King William Street, London, E.C.4. (Tel.: Avenue 7333/8.)

Corrigendum

Pressure and Flow Distribution in a Model of a Venturi-Type Open-Hearth Furnace

The following correction should be made to the paper by J. A. Leys and E. T. Leigh (*Journal of The Iron and Steel Institute*, 1950, vol. 165, July, pp. 301–306):

Page 302, right-hand column, the first equation should read

$$\Delta E = (p_1 + \tfrac{1}{2}\rho\overline{V}_1^2) - (p_2 + \tfrac{1}{2}\rho\overline{V}_2^2)$$

DIARY

6th July–30th Sept.—INSTITUTION OF METALLURGISTS—Metallurgical Exhibition—Science Museum, South Kensington, London, S.W.7.

30th Aug.–6th Sept.—BRITISH ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE—Annual Meeting—Birmingham.

30th Aug.–7th Sept.—INDUSTRIAL FINISHES EXHIBITION—Earls Court, London, S.W.5.

11th–12th Sept.—UNESCO—International Meeting of the Associations for the Advancement of Science—Paris.

12th–15th Sept.—THE IRON AND STEEL INSTITUTE—Special Meeting—Glasgow.

12th Sept.—WEST OF SCOTLAND IRON AND STEEL INSTITUTE and THE IRON AND STEEL INSTITUTE—Joint Session—Glasgow.

12th–21st Sept.—SUMMER SCHOOL IN AUTOMATIC COMPUTING—Mathematics Laboratory, Cambridge.

19th–22nd Sept.—INSTITUTE OF METALS—42nd Annual Autumn Meeting—Bournemouth.

19th–23rd Sept.—INSTITUTION OF MINING AND METALLURGY—Conference on Wire Ropes in Mines—Ashorne Hill, Leamington Spa.

28th Sept.–1st Oct.—ASSOCIAZIONE ITALIANA DI METALLURGIA—4th National Congress—Florence.

TRANSLATION SERVICE

(The previous announcement was made in the August, 1950, issue of the *Journal*, p. 461).

TRANSLATIONS AVAILABLE

No. 404 (German). J. KLÄRDING and A. MEYER: "Deoxidation with Ferro-Aluminium in the Basic Bessemer Steelworks." (*Verein Deutscher Eisenhüttenleute, Confidential Report No.* 61, Mar., 1944).

No. 405 (Czech). F. SICHA: "The Influence of the Chemical Composition of Hypo-Eutectoid Steels on the Ac_3 Temperature and the Optimum Hardening Temperature." (*Hutnické Listy*, 1949, vol. 4, June, pp. 169–174).

TRANSLATIONS IN COURSE OF PREPARATION

(Czech). J. FORMÁNEK: "Briquetting of Lignite and Coal without Use of a Binder by the Dolni-Rychnov Method." (Bánský Obzor, 1949, vol. 3, July, pp. 97–99; Aug., pp. 121–123).

(German). A. E. LENDL: "Bevelling and Rounding-off in Roll-Pass Design." (Stahl und Eisen, 1949, vol. 69, Apr. 28, pp. 306–308).

(Spanish). F. MILLAN and F. BARBADILLO: "The Sintering and Preparation of Iron Ores at the Vizcaya Works of the Altos Hornos de Vizcaya, S.A." (Instituto del Hierro y del Acero (Journal), 1950, vol. 3, No. 1, Jan./Mar., pp. 47–53). (Abridged translation prepared by Mr. R. Sewell and made available through the courtesy of the Research and Development Department, The United Steel Companies, Ltd., Stocksbridge, near Sheffield.)

ABSTRACTS OF CURRENT LITERATURE *and* BOOK NOTICES

IRON AND STEEL MANUFACTURE AND RELATED SUBJECTS

CONTENTS

	PAGE
Mineral Resources	93
Ores—Mining and Treatment	93
Temperature Measurement and Control	94
Production of Steel	94
Heat-Treatment and Heat-Treatment Furnaces	94
Forging, Stamping, Drawing, and Pressing	95
Lubricants and Lubrication	96
Welding and Flame-Cutting	96
Cleaning and Pickling	96
Protective Coatings	97
Powder Metallurgy	98
Properties and Tests	99
Miscellaneous	100
Book Notices	101
New Publications	103

MINERAL RESOURCES

Iron Ore Deposits in Southern Portugal. J. M. da Silva. (Estud., Notas e Trabal., Servico Fomento Mineiro, 1948, vol. 4, pp. 31–41 [in French]: Chemical Abstracts, 1949, vol. 43, Aug. 10, col. 5708). Descriptions, with ore analyses, are given of titaniferous magnetite in gabbro, pyrometasomatic magnetite–pyrite deposits at the contact of diorite and crystalline limestone, hematite–limonite–manganese oxide deposits in quartz-barite veins, and hematite-quartz sedimentary deposits in pre-Cambrian rocks.

Hungarian Deposits Suitable for Producing Bentonite. O. Tittel. (Bányászati és Kohászati Lapok, 1949, vol. 4, Nov., pp. 490–495). [In Hungarian]. The prospects of finding suitable deposits for producing bentonite in Hungary are discussed and the attention of the Hungarian reader is drawn to the fact that the term ' bentonite ' is also used in Hungary for certain aluminium hydrosilicates which do not show the properties characterizing bentonite as understood in other countries.—E. G.

U.S. Steel's Answer to the Iron Ore Shortage. T. C. Campbell. (Iron Age, 1950, vol. 165, Mar. 2, pp. 75–80). The history of the discovery of the Cerro Bolivar iron ore deposits in Venezuela is given. This is a high-grade hematite–limonite body containing 57% iron: about 1500 million tons of ore are estimated to be available. After development of communications about 10 million tons a year will be shipped to the U.S.A.—J. P. S.

Chromite Deposits of Boulder River Area, Sweetgrass County, Montana. A. L. Howland, E. M. Garrels, and W. R. Jones. (United States Geological Survey, 1949, Bulletin 948-C).

Geology and Manganese Deposits of the Lucifer District, Baja California, Mexico. I. F. Wilson and M. Veytia. (United States Geological Survey, 1949, Bulletin 960-F).

Iron Ore of Brazil. (Mineração e Metalurgia, 1949, vol. 14, Nov., pp. 100–101). [In Portuguese]. This is a short note on a report to the First Annual Meeting of the Brazilian Society for the Advancement of Science, held in October, 1949. The seven types of Brazilian iron ore are listed: magnetite; cata-itabirite; itabirite (alternate hematite and quartz beds); compact hematite; jacutinga (a friable hematite); rubble ore; and canga (a laterite concentrate of iron hydroxides). Locations and estimates of reserves are given.—R .S.

ORES—MINING AND TREATMENT

Leaching Process—Recovery of Manganese from Low-Grade Ores. R. D. Hoak and J. Coull. (Chemical Engineering Progress, 1950, vol. 46, Mar., pp. 158–162). A process for recovering manganese from low-grade manganese ores by leaching with waste pickling liquor is described. Production of the manganese oxide concentrate involves four main operations: (1) Ground ore (ground to 60-mesh is convenient) is leached with pickle liquor and the sulphate solution is separated from the gangue; (2) the sulphate is converted to a chloride solution by treatment with calcium chloride, and the precipitated calcium sulphate is filtered off; (3) the optimum proportion of iron is separated from the pregnant solution by differential precipitation with chalk or pulverized high-calcium limestone; and (4) manganese is precipitated from the solution with high-calcium lime slurry. The precipitate is filtered off, washed, and dried as product, and the calcium chloride solution remaining is concentrated for re-use.—R. A. R.

Flotation of Gray Iron Ores from the Talladega Area, Alabama. H. G. Iverson. (United States Bureau of Mines, 1949, Dec., Report of Investigations 4570). Laboratory-scale trials of the flotation of Talladega iron ores are reported. The results obtained with and without magnetic separation were not as good as those obtained by the reduction-roasting and magnetic separation procedures employed by other investigators. In the main, recovery of iron by flotation was 80 to 90% and the grade of concentrate was 50 to 60% iron.
R. A. R.

Sintering Trials in the Pilot Plant of the Duro Felguera Metallurgical Company. M. Aybar Gallego. (Instituto del Hierro y del Acero, 1949, vol. 2, Oct.–Dec., pp. 44–51). [In Spanish]. After describing the plant (Greenawalt type), the author gives the chemical and screen analyses of the ores and fuels, and the quantities used for the mixtures. The quality of the sinter made and the percentage desulphurization obtained with the different mixtures of ores, pyrites cinder, and iron carbonates without calcining, are given. Trials were carried out over a period of four years.

Fines direct from the mines of Llumeres were used. The analysis was: Gangue 14·25%, SiO_2 13·0%, total Fe 48·33%, Mn 0·12%, CaO 1·52%, MgO 0·35%, Al_2O_3 4·61%, P 0·60%, S 0·075%, CO_2 1·95%, combined H_2O 1·98%, FeO 4·35%, Fe_2O_3 43·98%, and humidity 3·70%. The composition of the mixture was 77% fines, 19% returned fines, and 4% coke. Maximum humidity was 5%. Duration of sintering was 20–25 min. Typical analysis of finished sinter was: Gangue 22·12%, SiO_2 16·87%, total Fe 50·58%, Mn 0·20%: CaO 2·57%, MgO 0·45%, Al_2O_3 7·86%, P 0·48%, S 0·05%, FeO 12·0%, Fe_2O_3 37·98%, and humidity 0·80%.

Other ores used were from Granada (56% Fe); Rubio (Bilbao) (Fe 50%, S 0·85%); and 86% desulphurization was achieved; Rif ore (Fe 60%, S 0·29%); in this case 80% desulphurization was obtained; finally, Bilbao carbonate (Fe 39·9%, S 0·27%). The last showed the possibility of satisfactorily achieving roasting, desulphurization, and sintering of carbonate fines in a single operation.—R. S.

TEMPERATURE MEASUREMENT AND CONTROL

The Measurement of Flame Temperatures. P. Barret. (Publications Scientifiques et Techniques du Ministère de l'Air, 1950, Note Technique No. 33). This report is divided into two parts under the headings: (1) The influence of spherical aberration and diffraction on the measurement of flame temperatures by the line reversal method; and (2) experimental determination of isothermal surfaces in the Bunsen burner flame. A detailed and illustrated description is given of the experimental work and the following conclusions were reached: (1) Spherical aberration varying with wavelength can introduce variations of 50% in the temperatures given by different lines; (2) the radiation of metal vapours in all points of bunsen flame is purely thermal; (3) the measured temperature is independent of the anion joined to the alkaline cation by which the flame is coloured; (4) the measured temperature varies only slightly with the concentration of the metal vapour in the flame; (5) Féry's method, applying lithium, sodium, and cæsium lines to an acetylene flame, gave results agreeing with those of Kurlbaum's method; and (6) the essential conditions that the optical method must follow so that the temperatures measured by Féry's method may be correct, are now known.—J. C. R.

Controlling and Measuring Steel Temperatures in Billet Heating Furnaces. F. S. Bloom. (Iron and Steel Engineer, 1949, vol. 26, Nov., pp. 60–70). A review is presented of different methods of measuring steel temperatures in billet-heating furnaces and methods of controlling the operation of these furnaces by using these temperature measurements. Operational experience led to the following conclusions: (1) The continuous billet-heating furnace can be controlled by a steel-temperature-measuring controller. (2) Steel temperature measurement and control can eliminate 75% of personal vigilance. (3) At least 75% of slag conditions and scale build-up on the hearth of a conventional furnace can be eliminated. (4) Furnace production can be increased 10%. (5) Changes in furnace pressure and in fuel/air ratio are quickly apparent and maximum furnace efficiency can be maintained.—J. C. R.

Glass Pens without Platinum Tips. A. A. Nizovtsev. (Zavodskaya Laboratoriya, 1949, vol. 15, Dec., p. 1499). [In Russian]. A very brief description is given of a simple pen, made entirely of rubber and glass, for use in automatic recorders of temperature, etc.—S. K.

PRODUCTION OF STEEL

For Better Machinability—E Steel. F. T. Kent. (Iron Age, 1950, vol. 165, Feb. 2, pp. 79–81, 96). Jones and Laughlin E steel is a low-carbon (0·04–0·06%) free-machining steel made in the acid-Bessemer converter. A special low-carbon (1–3%) ferromanganese is used as a deoxidizer, and its action is much less violent than normal ferromanganese (6·7% carbon) and less liable to agglomerate and segregate inclusion-forming material: the inclusions beneficial to machinability are therefore kept in a finely dispersed and submicroscopic size. Machining of this steel, which is available in three manganese and sulphur ranges (Mn 0·6–0·9%, S 0·08–0·15%; Mn 0·7–1·0%, S 0·16–0·23%; Mn 0·70–1·0%, S 0·24–0·33%) shows that it is superior to conventional steels, *e.g.*, B1112 (C 0·13%, Mn 0·7–1·0%, P 0·07–0·12%, S 0·16–0·23%) in drilling, turning, and forming operations.—J. P. S.

Better Machinability with MX Steel. A. W. McLaren and L. W. Oswald. (Iron Age, 1950, vol. 165, Feb. 2, pp. 86–88). Carnegie Illinois MX steel is a low-carbon (0·08% max.) free-machining steel made in the acid-Bessemer converter. A special low-carbon ferromanganese is used, and melting practice is calculated to bring the sulphide inclusions into a globular form. The silicon content is considered of importance and a maximum silicon figure is worked to. Machining of this steel shows that it is superior to B1113 (C 0·13%, Mn 0·7–1·0%, P 0·07–0·12%, S 0·24–0·33%) in drilling, turning, and forming operations, and also in the crimping and curling operations performed on some machined parts.
J. P. S.

Developments in the Sphere of Steel Production. F. Pawlek. (Die Technik, 1949, vol. 4, Dec., pp. 569–573). The literature on improvements in steelmaking practice is briefly reviewed.
R. A. R.

Inductive Stirring in Arc Furnaces. I—Electrochemical Aspects. L. Dreyfus. (Jernkontorets Annaler, 1949, vol. 133, No. 9, pp. 371–384). [In Swedish]. Electrodynamic forces occur in all electric furnaces where current is passing through the bath. In normal arc furnaces these forces are, however, very small. The conditions are more favourable when current is flowing continuously through a bottom electrode, but the theory shows that a sufficiently strong stirring action can be obtained with the aid of external stirring coils only. The best solution is offered by multiphase overlapping bottom coils, fixed directly under the furnace bottom which is made of non-magnetic steel. The frequency of the alternating current should remain so low that the current losses in the bottom remain moderate, but at the same time high enough for a sufficiently strong stirring action to be obtained in the lower part of the bath which will cause complete mixing of the whole bath in a short time. The stirring of the bath also facilitates the removal of the slag. Two installations of stirring coils have been completed and the results have fulfilled expectations.—R. A. R.

Inductive Stirring in Arc Furnaces. II—Metallurgical Aspects. F. Nilsson. (Jernkontorets Annaler, 1949, vol. 133, No. 9, pp. 385–468). [In Swedish]. An inductive stirring coil on the bottom of a 15-ton basic electric arc furnace making special steels has been in operation at Hagfors, Sweden, since 1947. Full details of its construction are given. Six pairs of heats with and without inductive stirring, and relating to different qualities of steel, have been investigated. Analyses of the bath, including the oxygen content, and of the slag, together with temperature measurements, indicate that inductive stirring has an important influence on the uniformity of the bath and the reactions between steel and slag. The reactions during refining, particularly oxygen and sulphur removal, are discussed, and methods of sampling for oxygen tests are critically reviewed.

The temperature and the carbon content at the surface of the steel bath usually increase during the refining period, but when the stirring coil is working, uniform temperature and analysis are obtained throughout the bath, even a short time after adding deoxidizers and alloying elements. The use of the coil facilitates slagging-off practice, and the final removal of the remaining slag is secured. This stirring practice applied to basic arc furnaces gives a good clean steel, low in oxygen and sulphur, and the refining time is reduced. The economic aspects are examined by a statement of costs with and without inductive stirring. The paper has 45 figures comprising illustrations, line diagrams, graphs, and heat logs.—R. A. R.

HEAT-TREATMENT AND HEAT-TREATMENT FURNACES

Heat Treating Trends and Developments for 1949. H. E. Boyer. (Steel Processing, 1950, vol. 36, Jan., pp. 15–21. 44, 45). Modern heat-treatment furnaces of all types are described and many are illustrated; most of these were exhibited at the 1949 Metal Congress at Cleveland, Ohio.
R. A. R.

Cutting Costs—By Improved Heat Treating Methods. E. J. Pavesic. (Iron Age, 1950, vol. 165, Mar. 30, pp. 98–100). To ensure correct heat-treatment of tools and dies, it is essential that the material should be free from original defects and that the design should not create stress raisers, such as notches and sharp corners, or cause unequal stress distribution. Before hardening, tool steels should be in a fully annealed, spheroidized condition, and should be thoroughly hardened before tempering; high-speed steels may require a double tempering. Where tools require straightening, this should be done before the steel has completely transformed to martensite: hot straightening from the martempering bath is valuable.—J. P. S.

A Study of the Carburization Process with Special Reference to Gas Carburizing. D. S. Laidler and J. Taylor. (Journal of The Iron and Steel Institute, 1950, vol. 165, May, pp. 23–39). As a result of comprehensive experiments, on both laboratory and semi-works scales, a successful carburization process, using town gas as the carburizing medium, has been developed. The mechanism of the carburization process is discussed in the light of existing knowledge and of the results of experimental carburizations in pure carbon monoxide. The variables considered are steel composition, temperature, surface activation, and gas velocity. Gas-reaction/time and carbon-absorption/time curves are given, and a distinction

is drawn between the effects of the rate of carbon diffusion and the rate of gas reaction at the surface on carburization.

Early laboratory experiments with town gas showed the carburizing efficiency to be much reduced, owing to soot formation on the steel surface, even before that surface is saturated with carbon. Soot formation is virtually eliminated if the oxidizing constituents—oxygen, carbon dioxide, and water vapour—are removed. A light film of graphitic soot begins to form if the gas flow is in excess of that required to maintain carbon saturation at the steel surface, but it attains an appreciable thickness only after very many hours. Case-depth/time curves for a number of steels and different temperatures are given, and diffusivity coefficients are calculated. The effect and importance of linear gas flow over the steel surface, and also the lowering of the surface carbon concentration by following the active carburizing period with a soaking period in a neutral atmosphere, are discussed. Practical tests illustrate the high degree of uniformity attainable.

Semi-works scale trials are described, and the practicability of the method is demonstrated. As in the laboratory, so also in commercial containers, the 'purified' town gas gave no sooting trouble. As available methods for the removal of carbon dioxide were unsatisfactory for gas volumes handled in practice, a new method, described in the Appendix, was developed whereby both the oxygen and carbon dioxide contents are reduced by passing the gas over a barium compound catalyst.

Furnaces for Gas Carburizing, Design and Operation. S. L. Widrig and W. T. Groves. (Metal Progress, 1949, vol. 56, Aug., pp. 194–199). An account is presented of gas-carburizing practice at the Spicer Manufacturing Division of Dana Corp., Toledo, Ohio. Three of the furnaces used are divided into two zones of automatic temperature control and three into four zones of control. Carburizing at 1725° F. is followed by intermediate cooling to 1150° F., reheating to 1550° F. (all in one passage through a continuous furnace), oil-quenching, washing, and then tempering at 340° F. Gear teeth of SAE 8620 or 4320 steel showed a fine-grained, relatively low-carbon martensitic structure with some excess carbide in the surface zone. This carbide greatly increased the wear resistance without harming the impact properties, provided it did not accumulate in a grain boundary network.—J. C. R.

The Principle and Application of Induction Heating. O. Gengenbach. (Werkstatt und Betrieb, 1949, vol. 82, Dec., pp. 430–434). The principles of induction heating are explained, and the design of circuits and coils for various metallurgical applications are considered. In a comparison of foreign and German apparatus it is shown that there is room for some simplification of the latter.—R. A. R.

Induction-Hardening Processes. J. A. Redmond. (SAE Journal, 1950, vol. 58, Jan., pp. 60–62). Changes in depth of case round the contour of gear teeth induction-hardened at different power levels for different times are shown in several micrographs. The core structure can also be controlled by preheating.—R. A. R.

Induction Hardening of Gears. H. B. Knowlton. (SAE Journal, 1950, vol. 58, Jan., pp. 54–58). The hardness, strength, and causes of failure of hardened gear teeth are discussed with special reference to induction-hardened teeth. It is not necessary to produce a hard case following the exact contour of the tooth surface, nor to produce a soft core. It is necessary to produce a hard layer around the entire surface of the tooth including the fillet. This layer must be of sufficient depth to support crushing loads, and to ensure that the outer portion of the core is not near enough to the surface to be in a zone of high bending stresses, but the residual stresses must be carefully controlled.—R. A. R.

A Sheet-Annealing Furnace-Charging Machine. (Engineer, 1950, vol. 189, May 12, pp. 566–567 : Engineering, 1950, vol. 169, May 19, pp. 564, 565, 568). An illustrated description is given of a machine for charging annealing furnaces with boxes of sheets. It has recently been put in commission at the Shotton Steelworks of John Summers and Sons, Ltd. The machine travels on heavy rails at 19-ft. centres parallel with the length of the annealing shop, and it consists of an undercarriage with four heavy rails at right angles to the track which can be aligned with four similar rails in each of the furnaces. The machine is designed to accommodate two boxes of sheets, each weighing 53 tons, at a time, and these boxes can be moved on traversing carriages into and out of the furnaces on one side of the track, and on to cooling racks on the other side. Devices are incorporated which enable the boxes of sheets to be deposited on to packing pieces on each side of the rails in the furnace and the traversing carriage to be withdrawn on to the machine.—R. A. R.

Salt Baths for Annealing and Descaling. E. Hague. (Metallurgia, 1949, vol. 41, Dec., pp. 63–67). Some electrically heated salt-bath installations for heat-treating and descaling are described, and the advantages of modern salt baths are pointed out.—R. A. R.

FORGING, STAMPING, DRAWING, AND PRESSING

Selection of Forging As a Method of Fabrication. J. J. Sloan and L. R. Denny. (Iron Age, 1950, vol. 165, Jan. 19, pp. 70–75). The advantage of forgings for quantity production of aircraft parts is compared with other methods of fabrication. The design of special dies so that left and right hand parts can be made together, or multiple parts subsequently separated by sawing, is described.—J. P. S.

Forging Stainless Steels. L. F. Spencer. (Iron Age, 1950, vol. 165, Feb. 16, pp. 100–104). The author considers the forging of ferritic, austenitic, and martensitic grades of stainless steel. The ferritic grades are easiest to forge and have a higher thermal conductivity than other stainless steels, but are given to grain growth if they are kept too long at forging temperature. Martensitic grades can be hardened by heat-treatment and do not develop maximum corrosion resistance until heat-treated. Austenitic steels cannot be hardened except by cold-working : their susceptibility to intercrystalline corrosion makes it essential to avoid the 800–1500° F. (425–815° C.) range when working, as the carbides are most likely to form in this range. The relatively low thermal conductivity of all stainless steels makes careful heating essential, and the author describes suitable furnaces. To conclude the article, some suitable forging machinery, drop-hammers, forging presses, and forging rolls, are described.—J. P. S.

Cold-Rolled Set Screws *versus* Turned Automatic Set Screws. W. Buschmann. (Österreichischer Maschinenmarkt und Elektrowirtschaft, 1949, vol. 4, Dec. 31, pp. 463–468). The mass production of set screws by cold heading the blanks and rolling the thread is described, and the method is shown to be more economical than production in automatics.—R. A. R.

The Stamping Industry in 1949. J. C. McComb. (Steel Processing, 1950, vol. 36, Jan., pp. 22–23). Some recent innovations in the stamping industry are mentioned. These include : (1) Research work by the Carnegie Illinois Steel Corp. leads to the theory that steel with a considerable degree of plastic anisotropy is more suitable for producing certain unsymmetrical formations ; (2) the General Electric Co., Schenectady, has developed a method of piercing and blanking steel sheet using a column of oil for the punch ; (3) impact stamping with cast zinc alloy dies for short production runs ; and (4) the Boeing Aircraft Co. has developed a new technique for cutting stainless steel and duralumin parts in production runs of about 5000. The die is made from a steel rule, with a heat-treated edge, mounted on a plywood base and shaped to the contour of the desired blank.—R. A. R.

New Dinking Dies Lower Blanking Costs. T. A. Dickinson. (Steel Processing, 1950, vol. 36, Jan., pp. 31–33). More details are given of the Boeing method of cutting stainless steel and duralumin blanks in thicknesses of about 0·04 in. which was referred to in J. C. McComb's review of the stamping industry (*see* preceding abstract). A pattern for the blank or part is cut out of $\frac{3}{4}$-in. plywood and a hardened and tempered steel strip is fixed round the edge of the plywood, the edge of the steel projecting to perform the cutting operation when the sheet metal is pressed on to it. Neoprene or other elastic material is glued alongside the edges of the steel strip to act as the knockout or stripper. Some cost data for production runs of 100, 500, and 2500 are given.

R. A. R.

Blanking Sheet Metal Parts with Steel Cutting Rules. E. Carpenter. (Iron Age, 1950, vol. 165, Jan. 12, p. 51). The use and construction of 'dinking' dies, on the general lines of a pastry-cutter, for cutting parts from sheet aluminium, duralumin, and stainless steel up to 0·040 in. in thickness is described. The material is mild steel, oil-quenched and tempered.—J. P. S.

Marform. A New Press Drawing Tool. T. E. Lloyd. (Iron Age, 1950, vol. 165, Feb. 16, pp. 78–81). In the Marform Process developed by the Glenn L. Martin Co., sheet is formed into cups, etc., by pressure between a forming punch and a rubber pad. The sheet is held between the rubber pad and a flat plate, through a hole in which the punch emerges. Steel up to 0·102 in. thick has been formed in this manner. Hydraulic presses are at present in use, but it is believed that mechanical presses could be employed.
J. P. S.

Electrical Drilling of Diamond Dies. J. Walter. (Przeglad Techniczny, 1948, vol. 69, Apr. 15, pp. 126–127). [In Polish]. The production of diamond dies by means of an electric arc is discussed and the ten operations involved are described.
W. J. W.

Mathematical Study of Wire-Drawing. J. Roubeaud-Valette. (Bulletin d'Information et de Documentation de l'Association Technique de l'Acier et des Métaux Non-Ferreux, 1949, vol. 3, Dec., pp. 5–38). This is a mathematical study of the theory of wire-drawing, of back-pull, and of the shape of the dies.—R. F. F.

LUBRICANTS AND LUBRICATION

How to Choose Wire Drawing Lubricants. E. L. H. Bastian. (Iron Age, 1950, vol. 165, Mar. 9, pp. 65–69, 86). Lubricants used for the drawing of ferrous and non-ferrous wires are described. Low-carbon steel wire may be lime coated and drawn with dry soap lubricant, or, if drawn wet, may be copper or tin-coated and drawn with soap-fat emulsions as lubricant. High-carbon steel wire is drawn in the same way as low-carbon, or it may be drawn hot, with graphite as lubricant. Stainless steel wire, usually drawn through carbide or diamond finishing dies, may be lubricated with heavy drawing oils and chemical compounds, or with low-viscosity oils and special aqueous emulsions.—J. P. S.

Metal Drawing Demands Correct Lubrication. E. L. H. Bastian. (Iron Age, 1950, vol. 165, Feb. 16, pp. 83–89). Types of lubricant for drawing operations are described and classified. In the case of stainless steel, although for ordinary press work the same lubricants may be used as for carbon steels, *i.e.*, soaps and fatty mineral oil blends, for deep-drawing chemically active oils and waxes are desirable. Chlorinated oils and waxes are easier to remove than dry solid non-metallic lubricants.—J. P. S.

WELDING AND FLAME-CUTTING

The Welding of Steel and Cast Iron. B. Hedde d'Entremont. (Métallurgie, 1949, vol. 81, Nov., pp. 31, 33, 35; Dec., pp. 19, 21, 23, 25). A general survey of welding methods and techniques is presented.—J. C. R.

General Remarks on Covered Electrodes for Welding Plain Carbon Steels. R. Diez Torres. (Boletin de Informacion del Instituto de la Soldadura, 1949, No. 2, pp. 32-35). [In Spanish]. The author comments, in a general manner, on the importance of a correct choice of electrodes, the necessity for limiting the number of types of electrodes, and the question of alternating and direct current. The mechanical properties of the weld metal are discussed in relation to the type of weld required. Finally, he suggests that standard methods should be established for testing welds, that metals for welding should conform to certain standards, and that electrodes should be standardized.—R. S.

First Annual Meeting of the Spanish Institute of Welding, 18th to 25th October, 1948. (Boletin de Informacion del Instituto de la Soldadura, 1949, No. 2, pp. 1–12). [In Spanish]. A summary of the work dealt with at various sessions is given. This includes: A review of British and American work on ductility and transformation temperatures; residual stresses; the teaching of welding; classification of electrodes (the present Spanish classification is of commercial importance only and a new classification is required); and applications of welding. Four study groups were set up to deal with weldability of steels, residual stresses, electrodes, and training.—R. S.

Alternating Current and Direct Current in Electric Welding. D. Cacharron Armesto. (Boletin de Informacion del Instituto de la Soldadura, 1949, No. 2, pp. 44–46). [In Spanish]. The author considers the pros and cons of alternating and direct current and explains the reasons for preferences in the case of certain jobs. He concludes that, whilst the use of the latter is to be preferred for the more delicate operations such as welding of stainless steel, aluminium, and bronze, identical results are obtained whichever is used on normal welding jobs.—R. S.

Weldability of Metals. M. Miro Ramonacho. (Boletin de Informacion del Instituto de la Soldadura, 1949, No. 2, pp. 23–31). [In Spanish]. The aim of this article is to fix certain fundamental conceptions, to enumerate the phenomena which occur during welding, and to describe the tests required to study these. Tests for determining the intrinsic qualities of base metals and of weld metals, and the weldability of loose and fixed members, are described. The methods of welding steels and non-ferrous metals are given and the following types of test for metallurgical weldability are described: Metallographic; hardness; micro- and macro-mechanical tests; and tests on welds under special conditions. Finally, the standardization of inspection for weldability is discussed.
R. S.

Weldability of Structural Steels in Relation to Carbon Content. L. B. Aznar. (Boletin de Informacion del Instituto de la Soldadura, 1949, No. 2, pp. 13–23). [In Spanish]. The two aspects of weldability are: operational weldability (study of the difficulties of joining), and metallurgical weldability (study of the base metal, zone of fusion, and phenomena affecting mechanical properties). The effect of carbon on the weldability of iron–carbon alloys is discussed, based on a comparison of the properties of the weld and the base metal. Some examples of the welding of semi-hard steel axles and cast steel wheels and of a 0·65% carbon chromium–nickel cast steel are described.—R. S.

Weldability of Mild Steel and Low-Alloy Steel. P. C. van der Willigen. (Lastechniek, 1949, vol. 15, Dec., pp. 317–321). [In Dutch].

Low Cost Manufacture of Large Diameter Pipe. P. J. Abel. (Iron Age, 1950, vol. 165, Jan. 26, pp. 77, 79–82). The plant of the Basalt Rock Co., Napa, Calif., was set up to produce seam-welded pipe from sheet nearer to the point of consumption than other plants run in conjunction with plate mills. Pipe sizes from 12¾ to 30 in. in dia., of ¼-in. and ⅜-in. wall thickness are made. The plant is fully described, including the pressing, welding, facing, and testing stages.
J. P. S.

CLEANING AND PICKLING

Action of Inhibitors in the Acid Pickling of Steel. Part I. M. Smialowski and J. Foryst. (Prace Badawcze Glownego Instytutu Metalurgii i Odlewnictwa, 1949, No. 2, pp. 147–153. [In Polish]. Experiments have been carried out concerning the efficiency of the inhibition of three organic compounds (dibenzylsulphide, dibenzylsulphoxide, and thiocarbanilide) in the acid pickling of iron, steel, and other metals. Dibenzylsulphide and thiocarbanilide, when in concentrations of 50 to 80 mg./litre, completely inhibit the evolution of hydrogen during the pickling of mild steel in 2 *N* sulphuric acid at 40° C., but do not completely prevent the diffusion of hydrogen into the steel. The content of nickel ions in the acid solution increases the inhibiting efficiency whilst copper ions act in the opposite manner. The inhibiting efficiency of dibenzylsulphoxide in hydrochloric acid is greatest in the case of nickel, cobalt, and iron; it is less with chromium and aluminium, and lowest with zinc and manganese.—W. J. W.

Metal Polishing and Electro Brightening. E. E. Halls. (Product Finishing, 1949, vol. 2, Nov., pp. 14–29). Electrolytic polishing is found to be cheaper in labour costs but more expensive in materials, power, and equipment than mechanical polishing. Particulars are given of four processes for the electrolytic polishing of stainless steel with the following electrolytes: (1) Citric acid 10%, sulphuric acid 10%, balance water, temp. 100° C.; (2) orthophosphoric acid 52%, sulphuric acid 25%, water 23%, temp. 80–100° C.; (3) orthophosphoric acid 37%, glycerine 56%, water 7%, temp. 80° C.; and (4) orthophosphoric acid (sp. gr. 1·700) 38%, glycerine 56%, water 6%, temp. 95–100° C. P. Berger's electrolytic method of polishing brass pressings is also described.—R. A. R.

Electrical Resistance and Optimum Composition of Electrolytic Polishing Baths. E. Darmois, I. Epelboin, and D. Amine. (Comptes Rendus, 1950, vol. 230, Jan. 23, pp. 386–388). To determine the optimum composition of an electrolytic polishing bath, a number of solutions containing the selected ingredients in various proportions are prepared and charged with the same amount of metal by

electrolytic polishing; then, using these solutions as electrolytic polishing baths, the maximum resistance of the anodic layer is measured. This maximum resistance varies from bath to bath, and is itself at a maximum in the bath which gives the best polish, as shown by microscopical examination. This is explained on the basis of an anhydrous layer round the anode in which a strong electrical field is set up, and an aqueous medium elsewhere which provides the necessary conditions for solution and the transport of ions. This theoretical explanation prompted the study of the variation of the electrical resistance of the bath with varying initial concentration of aqueous perchloric acid mixed with acetic anhydride; curves showing this relation for various amounts of dissolved metal in the bath are given. A second diagram shows the variation of the optimum bath composition and of the perchloric acid concentration corresponding to maximum bath resistance as functions of the quantity of metal dissolved (iron, nickel, and their alloys).—A. E. C.

Overvoltage and Electrolytic Polishing. R. Audubert, M. Bonnemay, and E. Lewartowicz. (Comptes Rendus, 1950, vol. 230, Feb. 13, pp. 646–648). Previous investigations of the variation of the current density with the potential difference at the terminals of the electrolytic polishing bath had given non-reproducible results. The present experiments were made on 18/8 chromium–nickel steel specimens which were polished in mixtures of phosphoric and sulphuric acids. The anode potential was measured against a standard electrode. When the circuit was completed the system gradually became stable. The current density and the potential both tended towards a limit, which was reached all the sooner as the current density itself was increased. The results were perfectly reproducible. R. Audubert had previously proposed a relationship between overvoltage and current density, and an attempt was made to verify whether it applied to electrolytic polishing, having regard to the high current densities used. The experimental curve obtained has four regions in which individually Audubert's theory applies; the phenomena associated with each region are noted.—A. E. C.

Cut Wire Shot Lowers Peening and Cleaning Costs. D. A. Cargill. (Iron Age, 1950, vol. 165, Apr. 6, pp. 95–97). The advantages of using 'shot' cut from lengths of high-carbon spring steel wire as the abrasive in shot peening and cleaning are detailed. Known as 'cut wire shot' and made from SAE 1065 steel (C 0·60–0·70%, Mn 0·60–0·90%, P 0·04% max., S 0·05% max.) in the form of wire, it is heat-treated and cold worked to a tensile strength of over 112 tons/sq. in., and a Rockwell C hardness of 48–52. In use, the shot forms rapidly into spheres. Very great savings of shot and in the wear of the blast-cleaning equipment are noted. Examples are: the reduction of shot consumption from 39 lb./wheel/hr. of shot previously used, to 2·5 lb./wheel/hr. of cut wire shot; and increase of the life of the wheel blades from 36 to 88 hr. J. P. S.

Steel Shot Speeds Blast Cleaning, Shot Peening. L. J. Wieschhaus. (Iron Age, 1950, vol. 165, Feb. 2, pp. 82–85). Cast steel shot, made by a process not described in detail, has been tested against chilled iron shot, first on a shot breakdown tester, and then in field trials. Breakage in the breakdown tester was far less, and on field trials, cleaning castings, removing heat-treatment scale, etc., a performance superior to chilled iron shot was given, both as regards consumption of shot and as regards the finish produced. The wearable parts of the cleaning apparatus, as long as sand from castings was not being circulated as well, also lasted much longer.—J. P. S.

PROTECTIVE COATINGS

A New Method for Preventing the Corrosion of Metals in Electrolytes by a Single-Atom Layer of a More Noble Metal. O. Erbacher, W. Herr, M. Ebert, and H. von Babo. (Archiv für Metallkunde, 1949, vol. 3, Dec., pp. 409–413). Experiments were made to establish whether electrochemical exchange without local-cell effect really does lead to the complete covering of the less noble metal with a single atomic layer of the more noble metal. An affirmative answer resulted from the fact that complete corrosion protection was given by the complete coating of the surface of the less noble metal. The great rapidity with which this electrochemical exchange takes place leads to slight non-uniformity in the coating, and it is believed there is an optimum condition at which equilibrium is established between the electrochemical precipitation of the more noble metal and its re-solution in the electrolyte. This optimum condition is governed by the prevailing concentration of the cations of the more noble metal; this concentration is, however, a component of the metal-cation/complex-ion equilibrium. To establish this equilibrium it is necessary for the prevailing rate of supply of the more noble metal cations to be high enough to prevent the formation of local cells.—R. A. R.

Electroplated Coatings for Corrosion Protection. A. G. Sussex. (Australian Institute of Metals: Electroplating, 1949, vol. 3, Nov., pp. 97–99, 102). In this survey of electroplated coatings in relation to corrosion protection, the following aspects are considered: Factors promoting and controlling corrosion, the porosity of electrodeposits, and the protection afforded by typical electroplated coatings and by alloy coatings.—J. C. R.

The Physical and Engineering Properties of Electrodeposited Metals. J. S. Anderson. (Australian Institute of Metals: Electroplating, 1949, vol. 3, Nov., pp. 84–91; Australasian Engineer, 1949, Dec. 7, pp. 35–44). The engineering applications of electrodeposits are considered under the headings: Decorative surfaces, protection of base metals from corrosion, plating for increased surface hardness and reclamation of parts machined under size, stress in electrodeposits, hydrogen embrittlement, improved bearing properties, modified electrical and thermal properties, improved lustre and reflective properties, electrodeposition of alloys, electroforming, and miscellaneous applications.—J. C. R.

Protective Coatings for Iron and Steel. (Bulletin of the British Cast Iron Research Association, 1950, vol. 10, Mar., pp. 194–200). An alphabetical list of processes for providing protective coating for iron and steel, with brief notes on each, is presented.—J. C. R.

When and How to Line Process Vessels with Stainless Steel. R. G. Sloan, jun. (Chemical Engineering, 1950, vol. 57, Mar., pp. 117–121). Practical recommendations on the costs and methods of lining vessels with stainless steel are made. For total wall thicknesses up to 0·25 in. solid stainless steel is probably most economical, for thicknesses in the 0·25 to 0·75 in. range each case should be examined on its merits. For 0·75 in. and above, clad or lined construction is probably the best. Most of the paper gives details of several techniques by which the lining can be welded to the base metal.—R. A. R.

Experiments in Chromium Electrodeposition with Radioactive Chromium. F. Ogburn and A. Brenner. (Journal of the Electrochemical Society, 1949, vol. 96, Dec., pp. 347–352). To determine whether chromium is deposited directly from the hexavalent state or through the trivalent state in a used chromic acid bath, a radio-active isotope of chromium can be incorporated with either one or the other, and the radioactivity of the deposit should indicate from which state of valency the metal is deposited. A brief account of such experiments is given. The results showed that the chromium is deposited directly from the hexavalent chromium.—R. A. R.

Protection of Metals by the Diffusion of Chromium. P. Galmiche. (Comptes Rendus, 1950, vol. 230, Jan. 2, pp. 89–91). **New Process of Hot-Chromizing and Formation of Mixed Alloys by Diffusion.** P. Galmiche. (Revue de Métallurgie, Mémoires, 1950, vol. 47, Mar., pp. 192–200). In the process described the pieces to be protected are heated either in contact with a solid cementation powder consisting essentially of chromium or ferrochrome, aluminium or kaolin, and an ammonium halide, or else in the gas above such a cementation mixture. The ammonium salt decomposes, the halogen attacks the chromium, and the resulting vapour reacts with the metal under treatment, the chromium diffusing inwards. With a 0·1% carbon steel a chromium content at the surface of 50% can be achieved; the concentration decreases progressively from the surface. Using ammonium fluoride the coatings are perfectly bonded and are brilliant. This useful thickness, down to a content of 13% of chromium, can reach 0·1 mm. after 3 hr. at 1000° C. and 0·25 mm. after 6 hr. at 1100° C. Good protective properties are claimed. On high-carbon steels and cast irons the layers are harder than on mild steel; they can be nitrided to increase their hardness and resistance to chemical attack. By adding silicon, aluminium, or both to the cementation powder mixed coatings can be made.—A. E. C.

Self Regulating Solution Speeds Chromium Plating. W. Czygan. (Iron Age, 1950, vol. 165, Feb. 16, pp. 91–93). The

Unichrome self-regulating high-speed bath, made from a proprietary compound supplied by United Chromium, Ltd., New York, only requires making up with this compound to the desired specific gravity to be kept in constant balance for correct plating. Various users report increased cathode efficiency and fewer rejects.—J. P. S.

New Galvanizing Furnace Forms No Dross. M. Tama. (Iron Age, 1950, vol. 165, Apr. 13, pp. 93–96). The dross arising in the galvanizing process is described as an alloy of zinc containing 4% of iron dissolved from the work and from the kettle. A new type of furnace designed to minimize this eliminates the steel or iron kettle entirely. The metal is contained in a rectangular tank lined with refractory brick: from a point some two-thirds of the way up, a passage leads downwards and outwards to channels through a standard twin-coil Ajax low-frequency induction unit. Thus, heated metal circulates only in the upper portion of the hearth: the flow of metal is up the passage described, across the surface of the metal, and down the other side, returning to the passage well above the bottom: dross is thus able to fall undisturbed. Even temperature control and rapid heating are claimed: a 7-ton furnace heated by a 100-kW. inductor will produce the same output, of 1 ton of galvanized parts per hour, as a 10-ton iron kettle, and it is possible, by the use of more and more powerful inductors, to increase this to 20 tons/hr. J. P. S.

Addition Agents for Zinc Plating Solutions. (Electroplating, 1949, vol. 3, Sept., pp. 9–13). Data sheets are given listing a number of substances which are commonly added to the basic zinc plating solutions to assist in the production of bright deposits, to extend the bright current-density range, or to improve covering power at low current densities. The substances are subdivided under the headings of metals, sulphur compounds, other non-metals and colloids, and bright dips.—J. C. R.

Electroplated Tin–Zinc Alloy Coatings on Iron and Steel Components. E. E. Halls. (Metallurgia, 1949, vol. 41, Dec., pp. 68–73). The electrolytic process of depositing tin–zinc alloys, developed by the Tin Research Institute, is described, and the results of a number of comparative corrosion tests are cited. The two commonly used coating compositions are 50/50 and 80/20 tin–zinc. Anodes of the respective compositions are employed. The electrolyte is, in effect, a combination of the sodium stannate tin and zinc cyanide solutions. The cathode current density is 15–30 amp./sq. ft. and the bath is kept at 70° C. The soldering and resistance-welding properties of the coatings are also considered.—R. A. R.

The Behavior of Bituminous Pipe Coatings under Bending Vibrational Stress. W. Beck. (Corrosion, 1949, vol. 5, Dec., pp. 405–408). Lengths of steel tubing 1·38 in. in outside dia., 6 ft. 6 in. long with a wall thickness of 0·02 in. were held at each end in self-aligning bearings and rotated by an eccentric at one end to apply reversed bending stresses. Bitumen coatings prepared in different ways were applied to short lengths along the pipe; the coating was surrounded by a short length of aluminium tube, the intermediate space being filled with moist soil. An e.m.f. of 3 V. was kept constantly applied to the coatings during the test. Curves are drawn for changes in resistance against time and the number of stress reversals. Reinforced and non-reinforced coatings both showed brittle fracture and fatigue when exposed to oscillations at low temperature, whilst a petroleum grease did not. The vibration from heavy traffic is therefore likely to shorten the life of bitumen coatings on buried pipe lines.—R. A. R.

Rotodip and Rotospray at Morris Cowley. (Electroplating, 1949, vol. 2, Aug., pp. 533–539; vol. 3, Sept., pp. 18–20). An illustrated account is presented of the Rotodip method for cleaning, phosphatizing, and primer painting motor-car bodies as installed at the Cowley works of Morris Motors Ltd. The cycle of operations is: Cleaning by emulsion or alkali-type cleaner; cold rinse; hot rinse (140° F.); bonderizing; hot rinse (155° F.); final rinse with dilute chromic acid solution at 160° F.; thorough drying in an oven; cooling in air to painting temperature; dip priming; flash off and draining; and stoving. The body passes through the plant on a spit, which rotates as the work passes through the various tanks. Part II deals with the Rotospray finishing line which starts after the application and baking of the primer at the end of the Rotodip process. A special jig or trolley is used so that the operator may rotate the body so that every part can be reached with the spray gun or sander. The various steps in the finishing line are outlined.—J. C. R.

Metallizing for Corrosive Prevention. J. E. Wakefield. (Iron Age, 1950, vol. 165, Jan. 12, pp. 55–60). The general methods and applications of the spraying of zinc and aluminium for the protective coating of iron and steel structures are discussed. The author also notes the spraying of a corrosion-resistant hard-facing material known as Metco-Weld H which is applied in alternate layers with 18/8 stainless steel, Monel, or nickel, and then fused at 1950° F. (1065° C.) with a torch or by induction heating; this provides a non-porous coating.—J. P. S.

The Practical Application of the Metal-Spraying Process. H. Reininger. (Metalloberfläche, 1949, vol. 3, Aug., pp. A149–A155; Sept., pp. A173–A176; Oct., pp. A191–A195; Nov., pp. A207–A211; Dec., pp. A220–A223). In Part I the application of sprayed-metal coatings to provide protection against corrosion is reviewed with notes on the particular purposes of different non-ferrous metal and alloy coatings. Part II deals with heat-resisting coatings of aluminium, cadmium–aluminium, aluminium–silicon, and their heat-treatment for improving the protective properties. In Part III examples are given of the use of metal spraying to make parts and fittings previously imported by Germany. Part IV describes the manufacture of bearings with sprayed whitemetal surfaces, and the repair of journals by spraying steel on the prepared shaft. Some special applications are dealt with in Part V, and some correct and incorrect methods of surface preparation are described. There is a bibliography of 160 references.—R. A. R.

POWDER METALLURGY

Powder Metallurgy—Review of Progress during 1949. R. A. Hetzig. (Metallurgia, 1949, vol. 41, Dec., pp. 88–90). Progress in the uses of metal powders as reported by the recent technical literature is reviewed. Among the many magnetic, electrical, and heat-resisting applications cited is that of attempts to make a magnetic fluid clutch using a suspension of carbonyl iron powder in a suitable oil.—R. A. R.

The Application of Powder Metallurgy in Mechanical Engineering. J. Chudzinski. (Przeglad Techniczny, 1948, vol. 69, Apr. 15, pp. 129–130). [In Polish]. A brief review is given of production by and application of powder metallurgy in mechanical engineering, particular attention being given to self-lubricating bearings.—W. J. W.

How to Control Powder Part Size. E. E. Ensign and I. A. De Grote. (Iron Age, 1950, vol. 165, Apr. 20, pp. 83–86). A statistical study has been made of the variations in dimensions of a bushing made by powder metallurgy, of which the exactness of measurement, especially concentricity, was important. Control charts have been produced which enable the output to be held to dimensions.—J. P. S.

Pressing and Sintering of Metallic and Non-Metallic Powders. W. Rutkowski and H. Rutkowska. (Prace Badawcze Glownego Instytutu Metalurgii i Odlewnictwa, 1949, No. 2, pp. 111–125). [In Polish]. The pressing and sintering of iron, copper, iron–copper, copper–manganese, and iron–copper–manganese powders have been investigated. The metal powders were examined by different means. After mixing the powders with bakelite or steatite, different pressures were applied. The density obtained in relation to the applied pressure has been expressed by the equation: $\log s = a \log P + \log b$ where s is the density, P the pressure and a and b are constants to be determined for each mixture. Shrinkage or swelling was observed depending on the density of the sintered product. The sintering was carried out in hydrogen.—W. J. W.

Use of the Transverse Rupture Test to Evaluate a New Stainless Steel Powder. G. Stern. (Powder Metallurgy Bulletin, 1950, vol. 5, Jan.–Mar., pp. 15–16). Two new stainless steel powders (one with chromium 14%, and one with chromium 16·5% and nickel 8%) have been developed for making complicated shapes by powder metallurgy, and in their development the transverse rupture test of J. P. Scanlan and R. P. Seelig proved very useful for determining the green strength. Some test data are presented.—R. A. R.

Determination of Boundary Stresses during the Compression of Cylindrical Powder Compacts. E. Shank and J. Wulff.

(Transactions of the American Institute of Mining and Metallurgical Engineers, 1949, vol. 185, pp. 561–570 : Journal of Metals, 1949, vol. 1, Sept.). An experimental method is developed by which the non-hydrostatic pressures and shears acting on the interior wall of a cylindrical die can be measured. Such methods can be correlated with existing data to aid in the explanation of the pressing process.—R. E.

A Dilatometric Study of the Sintering of Metal Powder Compacts. P. Duwez and H. Martens. (Transactions of the American Institute of Mining and Metallurgical Engineers, 1949, vol. 185, pp. 571–577 : Journal of Metals, 1949, vol. 1, Sept.). Experiments are described which demonstrate the usefulness of the dilatometric method in studying dimensional changes which occur during the sintering of metal powder compacts. During the sintering of iron compacts the dimensional changes are greatly influenced by the allotropic change from α to γ iron.—R. E.

Powder Parts Add Up. P. Mondy. (Iron Age, 1950, vol. 165, Apr. 20, pp. 80–82). A number of parts used in a calculating machine are now made by powder-metallurgy methods.—J. P. S.

Powder Parts Machined and Plated. P. K. Scott. (Iron Age, 1950, vol. 165, Apr. 20, pp. 87–90). Machining operations to produce the lock for a ' parking meter ' from a cylindrical, flanged, and headed part produced by powder metallurgy are described. The intricate keyway is formed in the pressing process, but a transverse passage is drilled and broached, a special broach being used to remove only 0·0005 in. of metal per tooth. For satisfactory plating, the preliminary treatment involves solvent degreasing, lightly polishing and buffing, an alkali cleaning dip, a rinse, an acid dip, and another rinse. A coating of 0·0003 in. of copper is then given, in an acid copper bath. Final treatment is a nickel coating of 0·0005 in. followed by a chromium coating of 0·0001 in. No difficulty with porosity has been experienced and parts have resisted a 76-hr. salt-spray test.—J. P. S.

Oil Cavity Increases Self Lubrication. W. G. Patton. (Iron Age, 1950, vol. 165, Apr. 20, pp. 91–92). Powdered-metal bearings containing an internal cavity for lubricant are described ; this cavity, which occupies a considerable proportion of the cross-section, may be packed with absorbent sponge iron to retain and distribute the oil.—J. P. S.

Powder Helical Gears—They Said It Couldn't Be Done. A. J. Wayson. (Iron Age, 1950, vol. 165, Apr. 20, pp. 93–94). Helical gears with a helix angle of 10–27° can now be made by powder metallurgy. These are spun out of the pressing die by synchronizing motions between the rotating punches and the die.—J. P. S.

How GE Buys Powder Parts. J. D. Carey and A. G. Pison. (Iron Age, 1950, vol. 165, Apr. 20, pp. 95–97). The General Electric Company, Bridgeport, Conn., tests powder-metallurgy parts either in the complete form as supplied, or machines complete parts from formed slugs. In either case, accelerated service tests are applied, as well as tests to determine tooth shear strength, radial crushing strength, density, hardness, and chemical analysis.—J. P. S.

Making Jet Engine Compressor Blades by Powder Metallurgy. G. Stern and J. A. Gerzina. (Iron Age, 1950, vol. 165, Feb. 23, pp. 74–77). The manufacture of compressor blades from iron powder is described. The stages are : moulding, sintering, coining, infiltrating with copper, heat-treating, straightening, and heat-treating again. Tensile strengths of 40 tons/sq. in., and elongations of 8% are recorded.—J. P. S.

The Use of Metal Powders in Engineering. H. W. Greenwood. (Machinery, 1950, vol. 76, Mar. 23, pp. 419–421). The uses of metal powders for metallic cements, as brazing and soldering powders, for metal spraying, as reducing agent in the thermit process, in the manufacture of aerocrete, for powder welding, and as magnetic clutch materials, are discussed.—R. F. F.

PROPERTIES AND TESTS

The Relation between the Work of Deformation and the Volume of the Specimen which Undergoes Deformation in the Tensile Test. F. Vitovec. (Berg- und Huttenmännische Monatshafte der Montanistischen Hochschule in Leoben, 1949, vol. 94, Dec., pp. 362–365). As soon as necking begins in the tensile test the proportion of the volume of the specimen contributing to the deformation becomes less than the volume in the gauge length and it decreases as necking proceeds. A method of calculating this decrease in volume from data obtained in a single tensile test is described.—R. A. R.

Investigation of Tensile Specimens with Drilled Holes. G. Malmberg. (Jernkontorets Annaler, 1949, vol. 133, No. 4, pp. 153–162). Tensile tests were carried out on drilled and slotted rectangular specimens of structural steel from 15 to 30 mm. thick and about 400 mm. long, with the width four times the thickness. Two parallel holes were drilled through each specimen vertical to the flat side and at equal distances from the opposite edges so as to leave a square cross-section between them ; slits were sawn from the holes outwards to the edges. The pairs of holes increased in size from 2 to 20 mm. in dia. When they were tested to fracture there was usually a transition from tough to brittle fracture, and the diameter of hole at which this occurred was a measure of the brittleness of the material.—R. A. R.

Anisotropy of Annealed Metals. A. Krupkowski and S. Kawiński. (Hutnik, 1949, vol. 16, Sept.–Oct., pp. 347–352). [In Polish]. A conception of coefficients of partial uniform elongation a'_h and a'_b has been introduced, the value of which may be easily calculated from the data of elongation on a fractured flat metal test piece.

The relationship of these coefficients of partial uniform elongation,

$$K_a = \frac{a'_h}{a'_b}$$

is the coefficient of anisotropy for polycrystalline metals. It is a constant value for a given annealed metal, provided that the individual layers have undergone annealing before the same degree of cold working.

In the drawn test bars, various layers of which have been submitted to different degrees of cold working, the coefficient K_a varies in a continuous manner from one layer to another. Some annealed metals, such as mild steel, brass, and aluminium, after previous cold working, show a distinct tendency towards anisotropy.—W. J. W.

On Indirect Methods for the Calculation of True Resistance to Breaking. A. I. Chipizhenko. (Zavodskaya Laboratoriya, 1949, vol. 15, Dec., pp. 1452–1457). [In Russian]. Five equations in use for the indirect determination of true resistance to fracture are critically examined and shown to be inapplicable to calculations relating to previously deformed metal specimens. It is suggested that for such calculations from tensile test data, allowance must be made for the degree of the preliminary deformation of the specimen in estimating the true reduction in cross-sectional area. Two equations for calculations for tempered and previously deformed specimens are presented and shown to give satisfactory results for specimens of steel, nickel, and non-ferrous alloys.—S. K.

Approximate Calculation of the Tensile Strength of Heat-Treated Steels as a Function of their Chemical Composition. R. Zoja. (Metallurgia Italiana, 1949, vol. 41, Sept.–Oct., pp. 229–236). Two formulæ are given for the determination of the tensile strength of quenched and tempered steels from their chemical compositions. These formulæ are valid only when the test-pieces have been subjected to one of the following heat-treatments : The steel must be (1) quenched with the maximum efficiency ; and (2) tempered for 3 hr. at 600° C. Only approximate indications can be obtained from the first formula, which is very simple, but may suffice in certain cases. The tensile strength values obtained with the second formula are accurate to within $\pm$ 7 kg./sq. mm. or to within $\pm$ 8% of the value obtained. As this formula is more complicated, tables are given showing the tensile strength variations against the amount of each element present. This formula has been applied to 71 different carbon and alloy steels, with the carbon, silicon, manganese, nickel, chromium, molybdenum, vanadium, and aluminium contents varying between wide limits, having tensile strengths between 56 and 124 kg./sq. mm.—R. F. F.

Determination of the Conventional Elastic Limit of Spring Strip during Pure Bending. V. Ya. Zubov. (Zavodskaya Laboratoriya, 1949, vol. 15, Dec., pp. 1486–1487). [In Russian]. A description is given of a method for determining the conventional elastic limit of spring strip by measurements of the residual deformations of specimens released after remaining bent for a given time. The strip specimens were bent to various curvatures by insertion in steel rings of known diameter, the residual deformations being determined from

detailed examinations of curvature after removal. Results obtained with steel strips by this method are used to show the influence on the elastic limit of the time of tempering at 350° C.—S. K.

On Plastic Bending. (Zavodskaya Laboratoriya, 1949, vol. 15, Dec., pp. 1458–1467). [In Russian]. In this article, comments on some recently published views on plastic bending are made by three authors. G. I. Pogodin-Alekseev criticizes the the assumptions made by M. P. Markovets that the radius of curvature of the inner face of the specimen being bent is equal to that of the mandrel, and that the displacement of the neutral layer can be neglected. Markovets replies, producing experimental evidence in favour of his equation, which he considers firmly established for Armco iron bars of square section. This author also states that criticisms of his equation made by V. P. Romanovskii are erroneous, since they were made without allowing for the change in the height of the bar during bending. Romanovskii re-examines his own equation in the light of criticisms made by I. P. Renne, concluding that, while it is satisfactory for most practical cases, further experimental work is necessary for its full confirmation.—S. K.

Theories of the Physical Structure of Metals. I. Piaskowski. (Hutnik, 1949, vol. 16, Sept.–Oct., pp. 355–365). [In Polish]. Theories concerning the density of electrons and the energy distribution of the electrons in an atom are discussed.—W. J. W.

A Double-Loop Indicator for the Photographic Recording of Dynamic Strains. L. A. Goncharskii. (Zavodskaya Laboratoriya, 1949, vol. 15, Dec., pp. 1488–1490). [In Russian]. A simple mechanical-optical device of low inertia for the photographic recording of rapidly changing strains is described. It consists essentially of a small mirror suspended from two slightly twisted loops of thread or wire which are kept under tension by a spring. Any relative movement of the loops causes the mirror to rotate until the new position of equilibrium is reached, the corresponding movement of the reflected spot of light being recorded on light-sensitive paper. The factors influencing the sensitivity and reliability of the device are considered; it is stated that oil-damping is only necessary for dealing with vibrations of frequencies greater than the order of tens of hertz.—S. K.

Internal Stresses Due to Surface Hardening. L. Locati and A. Ferro. (Metallurgia Italiana, 1950, vol. 42, Jan., pp. 22–29). [In Italian]. The authors have studied the formation of internal stresses during surface hardening. Some of the results obtained were checked mathematically. The influence of various factors of the heat-treatment and the effects of internal stresses are discussed.—R. F. F.

The Application of Electrical Strain Gauges and Brittle Lacquers to Engineering Design. J. S. Caswell. (Metallurgia, 1950, vol. 41, Jan., pp. 165–170). The use of electrical strain gauges and brittle lacquers for determining stresses is explained. Resistance strain gauges of minute size coupled in suitable electronic circuits incorporating a cathode-ray oscilloscope and a timing circuit of appropriate frequency now enable studies to be made of stress-frequency cycles up to 50,000/sec.

The brittle-lacquer method can be applied to locate the zone or zones of high stress, and to indicate the directions of the principal stresses in these zones.—R. A. R.

Method for the Experimental Investigation of Deformation in Shearing. S. E. Khanin. (Zavodskaya Laboratoriya, 1949, vol. 15, Dec., pp. 1492–1494). [In Russian]. An optical method for measuring the deformations taking place in a flat specimen subjected to shearing stresses is described.

S. K.

The Fatigue of Metals. M. Roš. (Metallurgia Italiana, 1950, vol. 42, Jan., pp. 7–21). [In French]. The author discusses mathematically the fatigue of metals and the various factors connected with fatigue.—R. F. F.

The Yielding and Strain-Aging of Carburized and Nitrided Single Crystals of Iron. H. Schwartzbart and J. R. Low, jun. (Transactions of the American Institute of Mining and Metallurgical Engineers, 1949, vol. 185, pp. 637–645 : Journal of Metals, 1949, vol. 1, Sept.). A yield point was found in single crystals of iron containing small amounts of carbon or nitrogen. The yield point in polycrystalline iron is therefore not due to the presence of a grain-boundary film as has been frequently suggested. Strain-ageing was observed in single crystals of iron containing small amounts of carbon or nitrogen. The yield-point effect is increased by strain-ageing in single crystals just as it is in polycrystalline irons.

R. E.

Micrographic Confirmation of the Reversibility of the Transformation Producing Temper-Brittleness in Steels with Low Nickel and Chromium Contents. P. A. Jacquet. (Comptes Rendus, 1950, vol. 230, Feb. 13, pp. 650–651). Microstructures of a low-alloy steel (carbon 0·3%, nickel 3·25%, chromium 1·65%) showing the effect of passage from the brittle to the tough condition and from the tough to the brittle condition are illustrated. The heat-treatments applied to produce the four structures as indicated, and the features observed in the micrographs are briefly discussed. The embrittling transformation affects the whole volume of the grains. A constituent deposited in a compact mass, as an edging following more or less closely the intergranular network, disappears progressively; it is thought that one of the elements of this constituent diffuses to the joints and is precipitated there. (*See* next abstract of paper by A. R. Weill).—A. E. C.

X-Ray Study of the Temper-Brittleness of a Steel with Low Nickel and Chromium Contents. Adrienne R. Weill. (Comptes Rendus, 1950, vol. 230, Feb. 13, pp. 652–654). An X-ray investigation of the transformation producing temper-brittleness in low-alloy steels is described. The steel examined contained carbon 0·3%, nickel 3·25%, and chromium 1·65%. The conclusion is drawn that the element responsible for temper-brittleness enters into solution in the ferrite lattice during tempering in the sensitive region, and causes large distortions accompanied by internal stresses on it. This would agree with P. A. Jacquet's conclusion (*see* preceding abstract), *i.e.*, diffusion followed by precipitation at the grain boundaries of the element entering into the ferrite lattice, thus producing temper brittleness. Though direct precise evidence is still lacking, it is thought that temper-brittleness is caused by carbon. The part played by the alloying element (chromium, manganese, molybdenum, or tungsten) is fundamental to the solution, migration, and coalescence of the constituent carrying the carbon.—A. E. C.

MISCELLANEOUS

Control of the Quality of Steel Plant Products. K. Radzwicki. (Hutnik, 1949, vol. 16, Sept.–Oct., pp. 366–370). [In Polish]. The author gives a brief account of the control of the quality of steel-plant products. The purpose of the production records for each particular cast is suggested and the items in these records are discussed.—W. J. W.

The Application of Statistical Methods to Industrial and Metallurgical Research. A. Palazzi. (Metallurgia Italiana, 1949, vol. 41, Sept.–Oct., pp. 237–249). The author surveys the theory and the simplest application of statistics to industrial and laboratory research. This survey was limited to practical examples and large specimens. The most important statistical parameters and their calculation are mentioned as well as the important criteria for the statistical comparison of two series of experiments.—R. F. F.

Zinc and Iron. A. Kutzelnigg. (Archiv für Metallkunde, 1949, vol. 4, Dec., pp. 438–440). The frequency with which iron and zinc occur together in nature and some results of this are referred to, particularly the interference of each metal in the smelting and refining of the other. The manner in which these metals affect the formation of chlorophyll in vegetation is briefly discussed.—R. A. R.

Cutting Costs—By Standardizing Tool Materials. E. Griffiths. (Iron Age, 1950, vol. 165, Mar. 30, pp. 94–97). The Westinghouse Electric Corp., Pittsburgh, has developed a scheme of tool standardization intended to reduce the quantity and number of types of tool steel stocked and used, to determine the standard sizes required, to control material arriving to their own specifications and to provide data for heat-treatment procedures. The number of grades and sizes handled has been reduced from 1877 in 1940 to 370 in 1949.

J. P. S.

Steel Mill Purifies Waste Water. W. Czygan. (Iron Age, 1950, vol. 165, Feb. 23, pp. 82–84). Waste water from the blooming mill of the Alan Wood Steel Co., Conshohocken, Pa., goes first to an oxide concentrator where the bulk of the

mill-scale and oils is removed, and then to a Dorr classifier. Sludge from the concentrator, the classifier, and the neutralization of pickling wastes is dumped in a quarry : the water, plus make-up water from the Schuylkill River, is returned for further use.—J. P. S.

The Effect of Temperature on Steel Gas Cylinders. K.-F. Mewes. (Schweissen und Schneiden, 1949, vol. 1, Dec., pp. 212–214). The results of tests of the pressure increase with temperature of steel cylinders containing oxygen, acetylene, carbon dioxide, and liquefied gases are presented and discussed. Data are given for temperatures up to 100° C. In general, it is considered that normal heating of an oxygen or acetylene cylinder in the sun is not dangerous, but in the case of liquefied gases, especially when the cylinders are nearly full, the pressure increases to dangerous levels so that safety precautions are necessary.—R. A. R.

BOOK NOTICES

"*Härterei-technische Mitteilungen.*" Herausgegeben von Prof. Dr.-Ing. Riebensahm. Band 4, 1949. 8vo, pp. 164. Illustrated. Munich, 1950 : Carl Hanser-Verlag. (Price DM 19.50)

This volume is a collection of nine papers given at the Fourth Symposium on Hardening Matters organized by the Wissenschaftlich-Technische Arbeitsgemeinschaft für Härterei-Technik und Wärmebehandlung (Scientific-Technical Association of Workers in Hardening and Heat-Treating Processes) in 1948.

The papers were as follows :

(1) "A Critical Consideration of the **S**-Curve as Representing the Transformations in the Cooling of Steel." W. Stuhlmann.

In order to ascertain the exact significance of the **S**-curve, the author considers the manner in which it is drawn up. Previous conceptions of **S**-curves are critically examined. Since later developments in the shape of the curve have tended towards that of a sickle, the author suggests that the American term 'T.T.T. curve' is more appropriate.

(2) "The Ageing of Hardened Steels." W. Stenzel.

Natural and artificial ageing are considered and the changes in structure and properties at above and below room temperature are discussed in detail. A critical survey of the usual processes of ageing treatments is given.

(3) "An Explanation of the Various Methods of Hardening and Heat-Treating Steel." P. Riebensahm.

The author defines and discusses the following kinds of hardening and heat-treating processes : Water-, oil-, and air-quenching ; interrupted quench ; step hardening ; hot bath hardening ; isothermal quenching ; primary hardening (direct quench from hot working heat) ; toughening treatment ; hardening and tempering. Temperature-Time curves are given, illustrating the conditions accompanying each type of treatment.

(4) "A Simplification of the Heat-Treatment of Case-Hardening Steel." K. Winterer.

Old and new methods of case-hardening and the effects on case and core structure are discussed.

(5) "New Methods for Avoiding Distortion in Carburising." H. M. Meingast.

The author considers the factors leading to distortion in hardening and some tests to determine the causes of distortion. A hood furnace is described and the methods for carburizing gear wheels in it are outlined. The wheels are secured in the furnace, a system of protector rings and separators being used. Carburizing paste is sprayed on the parts. Distortion is avoided and output is stepped up.

(6) "Tensile Properties of Various Steels Tempered to the Same Hardness." H. Müller.

Ten steels, including tool, ball-bearing, chisel, cutting, and free-machining qualitites, were examined. Six of the series were heat-treated to give the same Brinell hardness and the remaining four steels were treated to give a different hardness. All the steels were then tested for yield point, maximum stress, elongation, reduction of area, fatigue bend strength, notch toughness and stress to rupture. It was shown that low-alloy steels possess greater capacity for deformation for the same hardness, and that carbon steels could replace alloy steels in the case of small sections up to a certain tensile strength.

(7) "Influence of Heat-Treatment, Material and Type of Charging in the Heat-Treating Furnace on the Tensile Properties of a Gear Wheel." H. W. Meingast and H. Glaubitz.

The changes in tensile properties are studied in relation to various heat-treatments and depths of carburizing. These properties are also influenced by the manner of charging the stock in the heat-treatment furnaces. It is shown that neither the carbon content of the case nor the depth of carburizing have any effect on the wearing properties. The author states that his conclusions are valid only for the gear wheel under examination.

(8) "Problem of Hardness Testing and Tensile Testing of Gear Wheels." H. Glaubitz and H. M. Meingast.

Special tests for gear wheels are described. These give useful information on friction, wear and impact strength, and help to satisfy the necessity for a reliable comparison of wear tests on gear wheels. Some frequently accepted criteria are criticized.

(9) "Influence of Steel Quality and Heat-Treatment on Tensile Properties of EC 100." A. Müller.

The results of very extensive tests of the effect of varying heat-treatment on the properties of 1 to 1·5% chromium steels are examined.—R. Sewell.

Hayes H. "*Drop Forging.*" 8vo, pp. ix + 105. Illustrated. London, 1950. Sir Isaac Pitman and Co., Ltd. (Price 6*s.*)

This book is written for the skilled artisan in the shop, and it endeavours to give him an insight into the relationships between mechanical and metallurgical problems. A particularly pleasing feature is the easily digestible and direct manner in which practical hints and facts are presented without being burdened with metallurgical and engineering details.

The author begins by discussing briefly the interplay of the various trades and how there have been competitors to drop forging. Improved machining techniques have enabled castings partly to replace drop forgings in some fields. On the other hand, drop forging has encroached on the foundry trade with the development of drop stampings.

Early forms of 'kick stamps' and steam stamps and the development of modern friction drop stamps are described in a manner adequate for the practical operator.

The chapter on operations and methods deals with the setting of dies and the manipulation of the stock and describes the stamping of connecting rods, front and stub axles, half links for cables, etc., concluding with some remarks on trimming.

High-speed mechanical presses are compared with drop hammers. Advantages of the former include : High output ; comparative noiselessness ; large die surface ; it is easier to keep dies aligned due to well-guided press rams ; ejectors can be fitted ; less skill required in operators. One disadvantage of presses is that scale is pressed in, but this can be overcome by the use of induction furnaces for heating the stock. Presses are more costly than drop hammers and not as universal.

The chapters on the heat-treatment and metallurgy of drop forgings present some useful information which might not otherwise be readily available to the man in the shop.

Finally, there are some notes on the design and cutting of dies, polishing and clearance.

Foundations, furnaces, testing, pickling and sand-blasting are not dealt with, owing to limitations of space.

R. Sewell.

"*Iron and Steel Directory and Handbook, 1950.*" Sixth Edition. 8vo, pp. 302. London, 1950 : The Louis Cassier Co. Ltd. (Price 25*s.*)

The previous edition of this Directory and Handbook appeared as long ago as 1939, which makes the arrival of the new edition, containing as it does up-to-date information, more than welcome.

The Directory sections, which form a useful guide to buyers of iron and steel castings, pig iron and steel, include completely revised lists of British pig-iron manufacturers, some 2500 ironfounders, steelworks, steel founders and makers, and British iron and steel groups. Iron and steel trades associations and iron, steel, and engineering scientific and technical societies and institutions are also listed, with their addresses and the names of their secretaries.

The Handbook section contains a large amount of technical data for engineers, metallurgists, and iron and steel makers and users. The contents include a list of approximate analyses of the different grades of pig iron made by all the principal British makers; recommended compositions of nickel cast iron for various purposes; tables relating to weights, etc., of cast iron and steel stock; and standard specifications and typical analyses of ferro-alloys and alloying metals. Abstracts of the British Standard specifications for ferrous material, covering cast irons, wrought irons, and cast steels, tables of the analyses and mechanical test requirements of British Standard En wrought steels and of steels to aircraft and D.T.D. specifications, together with a number of conversion tables (temperature, metric-English, etc.) form a convenient source of reference for engineers and technicians.

The final section comprises a classified list of manufacturers engaged in the iron, steel, and allied trades, together with a list of their addresses, and should prove of constant use to buyers in the engineering and other iron and steel-using industries, and in foundries and steel works. Some 320 products are listed, ranging from abrasive wheels to X-ray films, and including such items as foundry blackings, furnaces of all kinds, refactories, steel plates, strip and wire, tube making plant, etc.—R. E.

RÄNTSCH, K. "*Genauigkeit von Messung und Messgerät.*" (Technisches Messen in Einzeldarstellungen. Bd. 5). 8vo, pp. 83. Illustrated. Munich, 1950: Carl Hanser-Verlag. (Price DM 8.80)

This work forms the fifth volume of a series entitled "Individual Aspects of Technical Measuring," edited by Dr. K. Bürger. The author, Dr. K. Räntsch, belongs to the Zeiss Works, and the book is a result of his decision to publish his lectures from a course on "Fine Measuring," and to give the reader the benefit of his many years o teaching in Jena.

The purpose of measuring a body is to express numerically the state in which that body exists. Any measurement must be reviewed critically as regards its accuracy. To do this, an intimate knowledge of the possibilities of error in scientific measurement is required.

The author first explains the basic conceptions of measuring and the factors on which precision depends, *e.g.*, senses of the operator, characteristics of the apparatus (direct recording or calculating). The proportion of "subjective" and "apparative" causes of variation in results obtained on the same object, by the same operator, and with the same apparatus will vary each time a measurement is made. Other types of error are accidental, systematic, controllable, environment (*e.g.*, temperature), and observational.

In view of the inadequacies of the observer, of the apparatus and of the environment, a measurement completely free from error is an impossibility.

The work covers the following aspects: Systematic and accidental errors; influence of temperature; propagation of systematic and accidental errors; lack of precision in apparatus; doubtfulness of measurement results and the effect of systematic error on correctness and of accidental error on reliability of results; reproducibility of results; theory of observational errors (average and scattering); calculation of quadratic scatterings; propagation and probability of error.

An appendix contains a list of conventional symbols and most important formulae, and a bibliography.

R. SEWELL.

TEED, P. L. "*The Properties of Metallic Materials at Low Temperatures.*" (Monographs on Metallic Materials, vol. 1). 8vo, pp. viii + 222. London, 1950: Chapman and Hall, Ltd. (Price 21*s.*)

This well written book is the first of a series of monographs on Metallic Materials published under the Authority of the Royal Aeronautical Society.

The first two chapters are of a general introductory nature and Chapter III deals with the change in mechanical properties of aluminium and aluminium alloys with decrease in temperature. The lowest temperature at which tests were carried out appears to have been — 200° C. and the majority appear to have been carried out between approximately — 70° and — 78° C. The author's view is that from the many experimental results that have been obtained it can be said that it is probable, but no more than probable, that, from the design point of view, all wrought aluminium alloys improve to a certain extent in consequence of being subjected to subnormal temperatures.

Chapter IV deals with the physical properties of ferrous alloys at various low temperatures down to — 253° C. Sections are devoted to iron and carbon steels, ferritic and austenitic nickel steels, austenitic chromium–nickel steels, and a number of miscellaneous steels. The author concludes that, with no exception, the ultimate stress of the ferrous materials dealt with increases at least down to — 182° C. and in many cases continues to do so though at a decreasing rate, down to — 253° C., the lowest temperature at which determinations have so far been made. With the carbon steels, elongation and reduction of area generally rise with decreases in temperature down to about — 80° C., but thereafter tend to fall, sometimes sharply, and at — 180° C. are generally small, while, in the few cases in which these properties have been measured at still lower temperatures, they are either completely absent or of minute proportions as compared with their room-temperature values.

The author emphasizes that results of tests obtained from welded test pieces apply to machined welded test pieces, and that it must not be assumed that unmachined welds will be equally satisfactory.

Chapter V considers the change in notched-bar impact value of carbon steels with decrease in temperature and with some characteristics of welds. Work so far carried out shows that if high notch resistance is required at a temperature lower than — 60° C. it cannot be obtained by the use of an ordinary carbon steel.

Chapter VI considers the change in notched-bar impact values of alloy steels with decrease in temperature. The author concludes that, as the sole alloying constituent, nickel has an outstanding influence in reducing decrease in impact resistance with diminishing temperature. The change in mechanical properties of magnesium alloys with decrease in temperature is considered in Chapter VII. The author concludes that although the influence of low temperatures on the alloys which have been subject to test is in no degree startling, it is comforting, and although many wrought ferritic steels undergo a dramatic increase in notch sensitivity at low temperatures, the magnesium alloys so far examined, although initially possessing a low notched-bar impact value, either retain this down to — 80° C. or suffer some not very large decrease in it.

In Chapter VIII the author considers the properties of copper and copper alloys at low temperatures and concludes that they behave very well and, to quote his words, "Man's oldest friend amongst the metals is indeed the most trustworthy one." The behaviour of nickel, zinc, tin, lead, and their alloys with decrease in temperature is considered in Chapter IX.

This monograph is a valuable contribution to the literature dealing with the properties of metallic materials at low temperature, in that the author has taken the greatest care to obtain his data from every available source and to present it in an attractive and easily digestible form.

J. FERDINAND KAYSER.

UNDERWOOD, L. R. "*The Rolling of Metals—Theory and Experiment,*" vol. I. With a foreword by Sir Andrew McCance. 8vo, pp. xv + 344. Illustrated. London, 1950: Chapman and Hall, Ltd. (Price 42*s.*)

The mechanism of the deformation of metals by rolling is receiving year by year more attention from research workers and rolling-mill engineers, and a book of reference to the already published work has been needed for some time. Until lately, almost all the advances in the knowledge of the subject have been made in Germany or the United States, as a glance at the bibliography of Dr. Underwood's book will prove. The position has been changed, however, by the rapidly expanding research programme of the British Iron and Steel Research Association—a programme which embraces both the fundamental and practical aspects of the rolling process.

This work had its beginnings under the auspices of the Rolling Mill Committee of the British Iron and Steel Federation and indeed started as a literature survey made

by Dr. Underwood. This survey was circulated as a confidential report to the Industry, and, although it was published in its original form by the Iron and Steel Institute in 1946 as part of Special Report No. 34 (First Report of the Rolling Mill Research Sub-Committee of the Iron and Steel Industrial Research Council), there was a clear need for a more detailed review which should be made available to a wide public. Dr. Underwood, in view of his painstaking abstracting of the many published papers, and his ability (already shown in his former book " Roll Neck Bearings ") for presenting the essentials of a paper in a concise way, was particularly qualified to undertake a comprehensive survey, and the book under review, being the first of a two-volume work, will be invaluable to everybody connected with the metal industries.

It should be understood that this first volume is a survey of theory and experiment in relation to the rolling process rather than a book on rolling-mill plant and operation generally. It may be that Volume II will deal with some of the practical aspects, particularly in design, but a glance at the Iron and Steel Institute's recently published " Bibliography on the Rolling of Iron and Steel " will show at once that only a small part of the total literature on the rolling mill is included in Dr. Underwood's bibliography.

The particular value, however, of the present volume is that the principal papers on rolling theory and experiment in English, German, French, and Russian are described in sufficient detail to obviate the need to refer to the originals, and Dr. Underwood is particularly to be thanked for the general service he has thereby rendered.

After an introductory chapter setting out the scheme of the book, Dr. Underwood describes the elementary theory of the forces acting in the region of contact between the material and the rolls and then goes on to discuss, under the title of Forward Slip, the relative movement of the strip and roll during the rolling process. Dr. Underwood gives the concept of forward slip considerable prominence and it is felt that this is rather unfortunate. Those who have carried out experimental work in rolling will confirm that forward slip is easily measured with a high degree of accuracy, but at present is quantitatively the most difficult to link to the existing theories of rolling. Moreover, by considering forward slip before dealing with the mechanism of deformation in rolling, Dr. Underwood is forced to compare experimental measurements of slip with a very elementary and approximate theory.

The chapter on the Flow of Material in Rolling is good, and deals in considerable detail with the published investigations using grids of lines and so on, for indicating the movement of the material. The work by MacGregor and Coffin in America is not, however, included although their results are probably more accurate than many of those given in this chapter. In general, these investigations fail because the grids are placed on outside surfaces of the rolled material and represent boundary conditions rather than the actual movements within the material itself.

The chapter on Yield Stress outlines some of the ways in which the stress-strain relationship can be determined, while Chapter VI deals with the Experimental Determination of Friction between the Roll and the Material both in hot and cold rolling.

The next two chapters describe the theories of rolling with particular reference to the rolling of sheet and strip, while the following chapter gives a few examples of the ways in which roll force can be calculated, particularly for hot rolling where roll flattening can be neglected. The last topic to be treated in the first volume is the calculation of roll force in cold rolling where the elastic flattening of the roll cannot be ignored.

In this volume, Dr. Underwood has surveyed the papers which were published up to about 1942, although mention is made of later papers in some cases. He has also contented himself with accurately reporting the views and work of others and has confined his own remarks to a few paragraphs at the end of each chapter. It is felt that he has been wise in this, bearing in mind the aim of his book.

A note of warning should, perhaps, be sounded : this is not an elementary book for those who want an introduction to rolling theory. It assumes a fair knowledge of the mechanics of metals and of stress analysis, but as an accurate and unbiased account of the present state of knowledge it deserves to become a standard reference book.—HUGH FORD.

WORKINGTON IRON AND STEEL COMPANY. "*Works Handbook.*" 8vo, pp. 46. Illustrated. Workington, 1949 : The Company.

This small handbook was specially written for the employees of the Workington Iron and Steel Company and gives the terms and conditions of employment, the openings available for education and training, the pension scheme, and the provision for welfare and personal health. Particulars are also included of the origin and development of the Company over the last 70 years. The main products are also listed.—R. E.

NEW PUBLICATIONS

AMERICAN METAL MARKET. "*Metal Statistics*, 1949." Forty-Second Annual Edition. Sm. 8vo, pp. 800. New York (1949) : American Metal Market Co. (Price $2)

AMERICAN SOCIETY FOR METALS. "*Mechanical Wear.*" Proceedings of Conference held June 1949, at Manchester Institute of Technology. 8vo, pp. 387. Illustrated. Cleveland, Ohio, 1950 : American Society for Metals. (Price $6.50)

AMERICAN SOCIETY FOR TESTING MATERIALS. "*Symposium on Effects of Low Temperatures on the Properties of Materials.*" Presented at a meeting of the Philadelphia District, American Society for Testing Materials, March 19, 1946. (Papers reviewed by authors in October, 1949). Special Technical Publication No. 78. 8vo, pp. 62. Illustrated. Philadelphia, Pa. (1950) : The Society. (Price $1.50)

ANGLO-AMERICAN COUNCIL ON PRODUCTIVITY. "*Internal Combustion Engines.*" Report of a visit to the U.S.A. in 1949 of a Productivity Team representing the Internal Combustion Engine Industry. La. 4to, pp. x + 83. Illustrated. London and New York, 1950 : The Council. (Price 2*s.* 6*d.*)

BAKER, H. W. Edited by. "*Modern Workshop Technology.*" Part II. "*Machine Tools and Metrology.*" Med. 8vo, pp. viii + 514, with 295 illustrations. London, 1950 : Cleaver-Hume Press, Ltd., 42A South Audley Street, W.1. (Price 32*s.*)

BRITISH ENGINEERS' ASSOCIATION. "*Classified Handbook of Members and Their Manufactures.*" 1950 Edition: Twenty-First Annual Edition. 8vo, pp. 655. London, 1950 : The Association.

BRITISH IRON AND STEEL RESEARCH ASSOCIATION. "*Specification for Heavy Duty Electric Overhead Travelling Cranes for Use in Iron and Steel Works.*" Prepared for the Steelworks Cranes Sub-Committee of the Plant Engineering Division. La. 4to, pp. 58. Illustrated. London, 1950 : The Association. (Price 15*s.*)

BRITISH STANDARDS INSTITUTION. B.S. 8 : 1950. "*Steel Tubular Traction Poles.*" 8vo, pp. 13. London : The Institution. (Price 2*s.*)

BRITISH STANDARDS INSTITUTION. B.S. 494 : 1950. "*Cold Drawn Seamless Mild Steel Boiler and Superheater Tubes.*" 8vo, pp. 8. London : The Institution. (Price 2*s.*)

BRITISH STANDARDS INSTITUTION. B.S. 512 : 1950. "*Hot Finished Seamless Mild Steel Boiler and Superheater Tubes.*" 8vo, pp. 9. London : The Institution. (Price 2*s.*)

BRITISH STANDARDS INSTITUTION. B.S. 1639 : 1950. "*Notes on the Simple Bend Test.*" 8vo, pp. 15. London : The Institution. (Price 2*s.*)

BRITISH STANDARDS INSTITUTION. B.S. 1647 : 1950. "p*H* *Scale.*" 8vo, pp. 12. London : The Institution. (Price 2*s.*)

BRITISH STANDARDS INSTITUTION. B.S. 1652 : 1950. "*Seamless Half-per-Cent Molybdenum Steel Boiler and Superheater Tubes.*" 8vo, pp. 9. London : The Institution. (Price 2*s.*)

BRITISH STANDARDS INSTITUTION. B.S. 1653 : 1950. "*Seamless Chromium–Molybdenum Steel Boiler and Superheater Tubes.*" 8vo, pp. 9. London : The Institution. (Price 2*s.*)

BRITISH STANDARDS INSTITUTION. B.S. 1654 : 1950. "*Electrically Welded Mild Steel Boiler and Superheater Tubes.*" 8vo, pp. 8. London : The Institution. (Price 2*s.*)

CHURCHILL, H. D. and J. B. AUSTIN. "*Weld Design.*" Demy 8vo, pp. 224. Illustrated. New York, 1949 : Prentice-Hall, Inc. (Price $6.65)

CLARK, F. H. "*Metals at High Temperatures.*" Pp. 350. Illustrated. New York, 1950 : Reinhold Publishing Corp. (Price $7)

COCKRELL, W. D. "*Industrial Electronic Control : a Guide to the Understanding of Electronic Control Circuits for Industrial Uses.*" 4to, pp. 385. London, 1950 : McGraw-Hill Publishing Co., Ltd. (Price 34*s.*)

ELLIOT, G. D. "*The Evolution of the All-Carbon Blast Furnace.*" (A reprint of a paper before a joint meeting of the Blast Furnace and Coke Oven Associations of the Eastern States and Chicago District, in Detroit, on October 21, 1949). La. 4to, pp. 39. Illustrated. London : Carblox Ltd.

FRANCON, M. "*Le contraste de phase en optique et en microscopie.*" 8vo, pp. 106. Illustrated. Paris, 1950 : Editions de la Revue d'optique théoretique et instrumentale. (Price 480 francs)

GAYNOR, F. "*Pocket Encyclopedia of Atomic Energy.*" 8vo, pp. 204. Illustrated. New York, 1950 : Philosophical Library. (Price $7.50)

GILL, E. T. and E. N. SIMONS. "*Modern Welding Technique.*" 8vo, pp. x + 276. Illustrated. London, 1950 : Sir Isaac Pitman and Sons, Ltd. (Price 21*s.*)

"*Gmelins Handbuch der anorganischen Chemie.*" 8. Auflage. Herausgegeben vom Gmelin Institut in Clausthal-Zellerfeld. System-Nummer 35. *Aluminium.* Teil A—Lieferung 8. "*Die ternären Legierungssysteme : Aluminium–Eisen–Kohlenstoff, Aluminium–Eisen–Silicium.*" 8vo, pp. 1235–1370. Weinheim/Bergstr. 1950 : Verlag Chemie G.m.b.H. (Price DM 30.–)

GOEDERITZ, A. F. H. "*Metallguss. Entwicklung der deutschen Metallgusstechnik.*" I. Teil. "*Die Werkstoffe.*" 8vo, pp. 250. Halle (Saale), 1950 : Verlag von Wilhelm Knapp. (Price DM 21.60)

GRIFFITH, R. H. "*The Practice of Research in the Chemical Industries.*" 8vo, pp. vii + 184. Oxford, 1949 : University Press. (Price 12*s.* 6*d.*)

"*Härterei-technische Mitteilungen.*" Herausgegeben von Prof. Dr.-Ing. Riebensahm. Band 4. 1949. "*Vorträge beim IV. Härterei-Kolloquium der wissenschaftlich-technischen Arbeitsgemeinschaft für Härterei-Technik und Wärmebehandlung E.V.* 1948." 8vo, pp. 164. Illustrated. Munich, 1950 : Carl Hanser-Verlag. (Price DM 19.50)

HILTON, B. R. "*Welding Design and Processes.*" 8vo, pp. 342. Illustrated. London, 1950 : Chapman and Hall, Ltd. (Price 36*s.*)

HOBART TRADE SCHOOL. "*Electric Arc Welding Procedure.*" 8vo, Troy, Ohio : Hobart Trade School. (Price $3)

INSTITUTE OF METALS. "*Metallurgical Applications of the Electron Microscope.* A Symposium held at the Royal Institution, London, on 16th November, 1949, and organized by the Institute of Metals in association with the Chemical Society, the Faraday Society, the Institute of Physics, the Institution of Electrical Engineers, The Iron and Steel Institute, the Physical Society, and the Royal Microscopical Society. (Institute of Metals Monograph and Report Series, No. 8). 8vo, pp. vi + 164. Illustrated. London, 1950 : The Institute. (Price 21*s.*)

INSTITUTION OF METALLURGISTS. "*Metals in the Service of Mankind.*" Exhibition held at the Science Museum, London, July to September, 1950. 8vo, pp. 137. London, 1950 : The Institution. (Price 1*s.*)

"*Iron and Steel Directory and Handbook* 1950." Sixth Edition. 8vo, pp. 302. London, 1950 : The Louis Cassier Co., Ltd. (Price 25*s.*)

LAWTON, V. H. "*Examples of Structural Steel Design to Conform with the Requirements of British Standard* 449 : 1948." (B.C.S.A. Publication No. 1, 1950). La. 4to. Illustrated. London, 1950 : British Constructional Steelwork Association.

LICKTEIG, E. "*Schrauben-Herstellung.*" 2. Auflage. (Stahleisen-Bücher Bd. 4). 8vo, pp. xiii + 244. Illustrated. Düsseldorf, 1950 : Verlag Stahleisen m.b.H. (Price DM 26.–)

LYNTON, R. P. "*Incentives and Management in British Industry.*" 8vo, pp. viii + 212. London, 1949 : Routledge and Kegan Paul, Ltd. (Price 15*s.*)

MACHU, W. "*Die Phosphatierung.*" Pp. 350, with 135 illustrations and 74 tables. 1950. Weinheim/Bergstrasse : Verlag Chemie. (Price DM 26.–)

MACKWORTH, N. H. "*Researches on the Measurement of Human Performance.*" (Medical Research Council, Special Report Series, No. 268). 8vo, pp. 156. Illustrated. London, 1950 : H.M. Stationery Office. (Price 4*s.*)

MARTIN, L. H. and R. D. HILL. "*A Manual of Vacuum Practice.*" 8vo, pp. x + 120. Illustrated. Melbourne, 1947 : University Press. (Price 10*s.* 6*d.*)

MELLON, M. G. "*Analytical Absorption Spectroscopy—Absorptiometry and Colorimetry.*" Pp. vii + 618. New York : John Wiley and Sons, Inc. (Price $9)

MILLENET, L. E. "*Manuel pratique de l'émaillage sur métaux.*" 8vo, pp. xvi + 130. Illustrated. Paris, 1950 : Dunod. (Price 420 francs)

MINISTRY OF HEALTH. "*Interim Report of the Departmental Committee on the Deterioration of Cast Iron and Spun Iron Pipes.*" 8vo, pp. vi + 48. Illustrated. London, 1950 : H.M. Stationery Office. (Price 3*s.* 6*d.*)

OPEN DIE FORGING INDUSTRY. "*Manual of Open Die Forgings.*" 8vo, pp. 181. New York : Open Die Forging Industry. (Price $3)

OSBORNE, A. K. "*Raw Materials of the Iron and Steel Industry.*" (P.O.A. Raw Material Survey Series, No. 1). London : Purchasing Officers Association. (Price 3*s.*)

"*Quin's Metal Handbook and Statistics,* 1949." Part I. "*Non-Ferrous Metals.*" Pp. 422. Part II. "*Iron and Steel.*" Pp. 196. Compiler F. B. Rice-Oxley. Oblong 32mo. London : Metal Information Bureau, Ltd. (Prices : Part I 10*s.*, Part II 7*s.* 6*d.*)

RÄNTSCH, K. "*Genauigkeit von Messung und Messgerät.*" Herausgegeben von Dr.-Ing. K. Bürger. Band 5). 8vo, pp. 83. Illustrated. Munich, 1950 : Carl Hanser-Verlag. (Price DM 8.80)

RÖMPP, H. "*Chemie der Metalle.*" 5. Auflage. Pp. 323. Illustrated. Stuttgart, 1949 : Franck'sche Verlagsbuchhandlung. (Price DM 12.–)

RUMMEL, K. "*Einheitliche Kostenrechnung auf der Grundlage einer vorausgesetzten Proportionalität der Kosten zu betrieblichen Grössen.*" 3. Auflage. 8vo, pp. xv + 216. Illustrated. Düsseldorf, 1949 : Verlag Stahleisen m.b.H. (Price DM 14.50)

SCHIMKE P. and H. A. Horn. "*Praktisches Handbuch der gesamten Schweisstechnik.* Bd. 2. *Elektrische Schweisstechnik.*" 5. Aufl. 8vo, pp. x + 444. Illustrated. Berlin, Göttingen, Heidelberg, 1950 : Springer-Verlag. (Price DM 28.50)

SKAUPY, F. "*Metallkeramik : Die Herstellung von Metallkörpen aus Metallpulvern, Sintermetallkunde und Pulvermetallkunde.*" 4. Aufl. 8vo, pp. 267. Illustrated. Weinheim/Bergstr., 1950 : Verlag Chemie G.m.b.H. (Price DM 19.–)

SPINK, L. K. "*Principles and Practice of Flow Meter Engineering.*" Pp. 416. Foxboro, Mass : Foxboro Co. (Price $7)

Steel and Britain's Future. A Special Issue of the Iron and Coal Trades Review, September, 1949. 8vo, pp. 246 + 118. London, 1949 : Industrial Newspapers, Ltd.

TAYLOR, E. R. "*Definitions and Formulae for Students : Metallurgy.*" Fourth Edition. Sm. 4to, pp. iv + 60. Illustrated. London, 1950 : Sir Isaac Pitman and Sons, Ltd. (Price 1*s.*)

VAN DER VEEN, H. "*Corrosie.*" Pp. 360. Illustrated. Delft, 1949 : Uitgeverij Waltman. (Price 11.75 florins)

VOGEL, F. "*Titan, seine metallurgische und chemische Darstellung.*" (Die Metallhüttenpraxis in Einzeldarstellungen. Band 5). 8vo, pp. 143. Halle (Saale), 1950 : Verlag von Wilhelm Knapp. (Price DM 8.60)

WEBER, R. L. "*Heat and Temperature Measurement.*" Pp. 432. New York : Prentice-Hall Inc. (Price $6.65)

WILSON, P. J., jun. "*Coal, Coke and Coal Chemicals.*" 8vo, pp. 509. New York : McGraw-Hill Book Co., Inc. (Price $8)

WORKINGTON IRON AND STEEL COMPANY. "*Works Handbook.*" 8vo, pp. 46. Illustrated. Workington, 1949 : The Company.

C. H. T. WILLIAMS, J.P.

CHARLES HENRY TRELEASE WILLIAMS was born at Consett, Co. Durham, in 1898. He was educated at Doncaster Road and South Grove Schools, Rotherham, and at the Applied Science Department of Sheffield University.

In 1912 Mr. Williams entered the works of The Park Gate Iron and Steel Company, Limited, as an apprentice in the Electrical Department, and after five years he became an engineering draughtsman. In 1918 he served with the Machine Gun Corps, but returned to Park Gate Works on demobilization in 1919, to receive further training under Mr. Fred Clements. In 1923, at the age of twenty-five, Mr. Williams became Rolling-Mills Superintendent, and from then the story is one of steady progress to his Company's boardroom : he was successively appointed Assistant Works Manager in 1928, Works Manager in 1936, Director and General Manager in 1945, and Joint Managing Director in 1948.

Mr. Williams has always taken a keen interest in the technical development of the iron and steel industry, particularly on the engineering side. He is a Member of Council of the British Iron and Steel Research Association, serves on the Association's Budget and Rolling Practice Committees, is a member of the Engineering Panel, and Chairman of the Civil Engineering Committee. He is also Vice-President of the Sheffield Section of the Institution of Production Engineers.

Mr. Williams became a Member of The Iron and Steel Institute in 1929. In 1950 he was elected Chairman of the Institute's Iron and Steel Engineers Group and an Honorary Member of Council. He is a Justice of the Peace for Rotherham.

Navana Vandyk

C. H. T. Williams, J.P.
Honorary Member of Council